# ISSUES OF SPECTRUM SENSING IN COGNITIVE RADIO BASED SYSTEMS

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## ABSTRACT

Cognitive radio (CR) is a promising technology to overcome the insufficiency of available communication spectrums. Such radios are able to sense the spectral environment and use this information to opportunistically provide wireless links that meet the user communications requirements optimally. To achieve the goal of cognitive radio, it is a fundamental requirement that the cognitive user (CU) performs spectrum sensing to detect the presence of the primary user (PU) signal before a spectrum is accessed to avoid interference from other wireless users. In this paper, three local spectrum sensing (LSS) methods, namely matched filtering, energy detection and PU signal feature cyclo-stationary based detection will be discussed. The discussion will highlight the methods' strengths and weaknesses, the parameters concerned and their feasibilities to CR-based overlay and underlay technologies. Cross layer functionalities related to spectrum sensing will also be presented. Shadowing and multipath at various locations can degrade the sensing mechanism of an LSS detector. To address this issue, *cooperative spectrum sensing technique* is investigated where several LSS detectors of CR-assisted systems can be coordinated to perform spectrum sensing cooperatively to gather channel information for better sensing reliability.

## 1. INTRODUCTION

The limited available spectrum and the inefficiency in the spectrum usage necessitate a new communication paradigm to exploit the existing wireless spectrum opportunistically. A recent spectrum occupancy measurement (Fig. 1) shows that a significant portion of the spectrum allocated to licensed services show little usage over time, with concentration on certain portions of the spectrum while a significant amount of the spectrum remains unutilized (Akylidiz, et al., 2006). Spectrum utilization can be significantly improved by adopting the concept of Dynamic Spectrum Access (DSA) where unlicensed or cognitive users (CUs) can temporarily utilize unoccupied bands but need to be sufficiently agile to vacate the space (time, frequency or spatial) once the licensed or primary users (PUs) are detected as not to cause harmful interference.

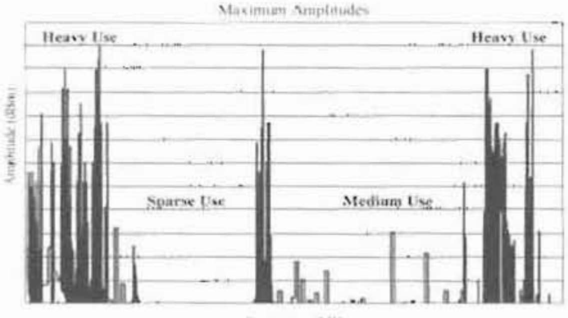

Fig. 1 Spectrum Utilization

Ultra-wideband (UWB) and cognitive radio (CR) are two exciting technologies that offer new approaches to spectrum usage. UWB is an underlay approach with restrictions on transmitted power levels; thus promotes coexistence with other existing radio technologies and operates over ultra wide bandwidth. While CR employs overlay approach based on avoidance of primary users by using spectrum sensing and adaptive allocations.

Originally introduced by Mitola, (2000), CRs are capable of sensing their environment, learning about their radio resources and user/application requirements, and adapting behavior by optimizing their own performance in response to user requests (Haykin, 2005). Researches in CR are mainly evolved around the following technical issues in enabling spectrum-aware communication protocols (H. Shiang & M. Schaar, 2008):

a) How to sense spectrum and model the behaviour of the PUs.
b) How to manage and decide the available spectrum to meet user QoS requirements. These management functions involve spectrum analysis and spectrum decision.
c) How to share the available spectrum resources fairly.
d) How to maintain seamless communication during transition (handoff) of selected frequency channels.

UWB is another promising technology for future short and medium range wireless communication networks with a variety of throughput options including very high data rates. Federal Communication Commission (FCC) in its report in 2002 authorized the unlicensed use of UWB in 3.1-10.6 GHz and has restricted the minimum occupied bandwidth of each mono/multi band(s) to 500 MHz. Furthermore, it defined a spectral mask that specifies the power level radiated by UWB systems within this band to be near the thermal noise floor (-41.3 dBm/MHz). The low power level makes UWB an attractive solution in WPAN multimedia applications as well as CR technology. It allows UWB to coexist harmoniously to share the spectrum with existing technologies such as 5 Ghz-U-NII bands without causing harmful interference by turning off UWB transmission on the occupied frequency bands. Thus, the corporation of CR feature of spectrum sensing is vital to locate spectrum holes, observe present users' activites and eventually avoid interference when transmitting. This hybrid technology, named Cognitive UWB (CUWB) is expected to exploit advantages of both CR and UWB for efficient spectrum resource management.

Furthermore, multiband orthogonal frequency division multiplexing (MB-OFDM) based UWB seems to be more attractive to CR technology due to the following characteristics (Rozeha, et al., 2008):

a) In MB-OFDM, subcarriers that are overlapped with PU can be turned off which results in flexible data rate.
b) Several users can coexists in the same temporal and spectral domain by assigning different Time-Frequency Code (TFC) which indirectly also provides information security.
c) Many of existing wireless standards such as IEEE802.11a/g WLAN, IEEE802.16 WIMAX and IEEE802.22 3GPP are based on OFDM technology. Hence, it offers seamless communications and interoperability among various wireless devices.

This paper is divided into five sections. Section 2 presents a review of well known spectrum sensing techniques, namely, matched filter, energy detector and cyclostationary feature detection. Section 3 presents the cross layer design of spectrum sensing and its intended functionalities. The principle of cooperative spectrum sensing is introduced in Section 4. Finally, open research challenges in spectrum sensing are discussed in Section 5.

## 2. SPECTRUM SENSING

To achieve the goal of CR, it is a fundamental requirement that the cognitive user performs spectrum sensing to detect the presence of PU signal. The spectrum sensing is often considered as a detection issue where the CUs have to scan a vast range of frequencies to observe available spectrum 'white spaces' or 'holes' that are temporarily and spatially out of service. The goal of spectrum sensing is to decide between the following two hypotheses (Akylidiz, et al., 2006):

$H_0$ : Primary user is absent

$H_1$ : Primary user is present.

In order to avoid harmful interference to the primary system, the sensing time should be carefully chosen. If the sensing time is too long, a PU may enter the band at which a CU is operating in and causes interference. In addition, lengthening the sensing time may result in missing chances for using the spectrum when a PU has left a band while the CU is still waiting for the sensing time to be elapsed. There are three aspects of PU detection that need to be verified and quantified in order to define metrics for CR systems (Rozeha, et al., 2008):

a) The time until detection of the PU.
b) The time needed to clear the spectrum once a PU has been detected.
c) The reliability of PU detection: the probability of missed detection, $P_{MD}$ and the probability of false alarms, $P_{FA}$.

If the detector mistakes $H_0$ for $H_1$, a false alarm occurs, and a spectrum opportunity is overlooked by the detector. On the other hand, when the detector mistakes $H_1$ for $H_0$, we have a miss detection, which potentially leads to a collision with PUs.

In general, CU sensitivity should outperform PU receiver by a large margin in order to prevent what is essentially a *hidden terminal problem*. This margin is required because CU does not have a direct measurement of a channel between primary user receiver and transmitter and must base its decision on its local channel measurement to a primary user transmitter. This type of detection is referred to as *local spectrum sensing* (LSS) and the worst case hidden terminal problem would occur when the CU is shadowed, in severe multipath fading, or inside buildings with high penetration loss.

LSS detector can be a matched filter, an energy detector, or a cyclostationary feature detector (Cabric, 2004), (Cabric, 2006). In this section, the advantages and disadvantages of each technique will be discussed.

### 2.1 MATCHED FILTER

The optimal way for any signal detection is a matched filter (MF), since it maximizes received signal-to-noise ratio (SNR). Due to its coherency, less time is required to achieve high processing gain since the number of samples required for optimal detection is O(1/SNR) (A. Sahai, et al., 2004). However, it requires a prior knowledge on the behavior (modulation) of the received signal. Hence, detecting different signals requires implementing several MFs.

### 2.2 ENERGY DETECTOR

The energy detector (ED) arises as a suboptimal choice for non-coherent detection using an estimated threshold (A.A. El-Saleh, et al., 2008). The ED requires no knowledge on the channel signals but a small error in estimating the hypothesis's threshold may result in an unreliable detection of PUs. Thus, the ED would completely fail in low SNR environments. Furthermore, the ED does not differentiate between modulated signals and noise. The number of samples required to optimally detect the incoming signal is $O(1/SNR^2)$ (A. Sahai, et al., 2004).

### 2.3 CYCLOSTATIONARY FEATURE DETECTOR

The cyclostationary feature detector (CFD) discriminates the modulated signals from the noise. CFD implements a two-dimensional spectral correlation function (SCF) rather than the one-dimensional power spectral density (PSD) of the energy detector to reliably extract the spectral correlation due to the periodicity feature of modulated signals from the noise that is of a wide-sense stationary (WSS) and no correlation (A.A. El-Saleh, et al., 2008). The main drawback for the feature detector is the increased complexity. Table 1 summarizes the strengths and weaknesses of each spectrum sensing techniques mentioned above.

Table 1 Advantages and Disadvantages of Spectrum Sensing Techniques

| Spectrum Sensing Technique | Advantages | Disadvantages |
|---|---|---|
| ED | Does not need prior information<br>Low computational cost | Cannot work in low SNR<br>Cannot distinguish users sharing the same channel |
| MF | Optimal detection performance<br>Low computational cost | Requires synchronization and a prior knowledge of the PU |
| CFD | Robust in low SNR<br>Robust to interference | Requires partial information of PU<br>High computational cost |

The feasibilities of each technique for overlay and underlay modes are also studied. Due to MF requirement of *priori* knowledge of the received signal and hence the need for several MFs to detect different signals makes it impractical approach for overlay system. However in underlay, it may be feasible by detecting the adjacent CU nodes using its preamble pattern as suggested in the proposed novel active sensing model by Qi. Liu et al. (2008). In the case of ED, due to its poor performance in low SNR environments, it is inconvenient to be utilized for the underlay CUWB which is mostly of low SNR (as it is so close to the noise floor level). However, it can be carefully used for the high-power overlay CR. Meanwhile, CFD can be considered as a strong candidate for both overlay CR and underlay CR-UWB technologies due to its capability of differentiating noise energy from the modulated signal energy.

## 3. CROSS LAYER DESIGN IN SPECTRUM SENSING

Cabric, et al. (2004) have proposed a cross design approach for spectrum sensing. This is to improve the CR sensitivity by enhancing radio frequency (RF) front-end sensitivity, exploiting digital signal processing gain for specific PU signal and network cooperation where CUs share their spectrum sensing measurements. The physical (PHY) and medium access control (MAC) layers' functions that are linked to spectrum sensing are considered. This is illustrated in Fig. 2.

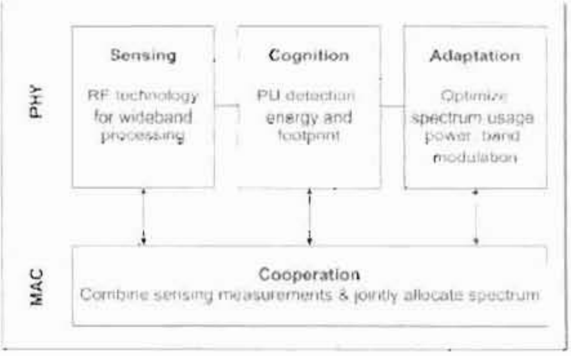

Fig. 2 Cross layer funtionalities related to spectrum sensing

## 4. COOPERATIVE SPECTRUM SENSING

There exist several open research challenges that need to be investigated for the development of the spectrum sensing function for underlay UWB. Because of the low emission power, its communication range is shorter than sensing range. Problems like hidden terminal, shadowing and fading environments may cause the miss detection if the existing active LSS methods are deployed. So these approaches are not proper for CUWB. Several recent works have shown that cooperative spectrum sensing can greatly increase the probability of detection in fading channels (A. Ghasemi & E. S. Sousa, 2005). Multiple CUs can be coordinated to perform spectrum sensing cooperatively and the sensing information exchanged between neighbors is expected to have a better chance of detecting PU compared to individual sensing.

A cooperative network of several CR-assisted systems can be modeled as an OR-rule network (A.A. El-Saleh, et al., 2008). The cooperation scheme used can be centralized or distributed. Work by R.W Brodersen, et al. (2004) has proposed a centralized scheme where an access point collects sensing results from all users. It then sounds the channel and performs channel allocation that meets the requested data rates of each user. In the distributed cooperation scheme as proposed by Cabric, et al. (2004), neighbors are chosen randomly. Although the implementation maybe easier, it does not achieve the capacity that of centralized scheme. A generic model of cooperative sensing is depicted in Fig. 3.

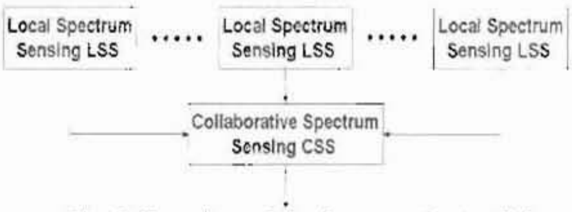

Fig. 3 Generic model of cooperative/ collaborative spectrum sensing

## 5. SPECTRUM SENSING CHALLENGES

The challenge of spectrum sensing in multi-user networks is raised in (Akylidiz, et al., 2006). Cooperative spectrum sensing technique can be utilized to exploit the multiuser diversity and independent fading channels (G. Ganesan & Y.G. Li, 2005). However, the remaining challenge in cooperation is combining the results of various users which may have different sensitivities and sensing times. A weighted combining method in (Lee, W. & Cho, D. H., 2008) is performed to take the differences into account. The need for control channel in cooperation, which can be either implemented as a dedicated frequency channel or as underlay UWB channel and overhead associated with sensing information exchange remain significant challenges.

Another challenge in spectrum sensing is developing an interference detection model by effectively measuring the interference temperature. In UWB, the spectrum sensing feature of the CR plays a role on the interference avoidance using various narrowband interference avoidance methods as described in (H. Arslan & M.E. Sahin, 2006).

One of the main requirements of cognitive networks is the detection of the PUs in a very short time (Akylidiz, et al., 2006). MB-OFDM has been introduced as a strong candidate to be the platform for underlay CR_UWB (A. Batra, S. Lingam & J. Balakrishnan, 2006). Since multi-carrier sensing can be exploited in OFDM-based cognitive networks, the overall sensing time can be reduced. Once a primary user is detected in a single carrier, sensing in other carriers is not necessary. In (H. Tang, 2005), a power-based sensing algorithm in OFDM networks is proposed for detecting the presence of a PU. It is shown that the overall detection time is reduced by collecting information from each carrier. However, this necessitates the use of a large number of carriers, which increases the design complexity. Hence, novel spectrum sensing algorithms need to be developed such that the number of samples needed to detect the primary user is minimized within a given detection error probability.

## CONCLUSION

Recent advances in technology have shown that Ultra-Wideband (UWB) and cognitive radio (CR) are two stimulating technologies that offer novel approaches to the spectrum usage. Hybrid technology, CUWB provides an ultimate spectrum aware communication paradigm in wireless communication. The discussion in this paper provides an overview of the spectrum sensing schemes for CR based systems. From the comparison, CFD seems to be the best detector for both overlay and underlay modes. A cross layer design established for spectrum sensing is also presented. Open research challenges in spectrum sensing are also discussed to facilitate further investigation for the development of spectrum sensing function.

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