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Term Paper

Cooperative Spectrum Sensing

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Cooperative Spectrum Sensing

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Abstract – In this paper, the problem of cooperative spectrum sensing is discussed in cognitive radio networks over Rayleigh fading and AWGN channels. The discussion takes into account the error in the decision reporting in analyzing the performance of cooperative spectrum sensing and the hidden terminal problem. Multiple methods which include cooperative diversity, relay diversity, multiuser diversity, and censored decision are discussed to improve the performance of cooperative spectrum sensing.

1 Introduction

1.1 Problem Background

In the past two decades, the explosion in the number of available wireless services and application had to congestion in the EM spectrum. The radio spectrum is a limited resources that needs to be regulated so only licensed users can use certain spectrum without any violations from any unlicensed users. This spectrum scarcity is conflicted by the underutilization of the primary licensed of their allocated spectrum. In a recent 2004 study, It was showed that NYC's spectrum was utilized only 13.1% of the time, some frequencies more the other, during the 2004 Republican National Convention. A possible solution to spectrum scarcity is to improve spectrum utilization by allowing secondary users to access under-utilized licensed bands dynamically when/where licensed users are absent. This concept is one fundamental basis for Cognitive Radios.

Cognitive radio is a new technology, which improves the spectrum utilization by allowing secondary users to use unused radio spectrum from primary licensed users or to share the spectrum with the primary users. Using Software Defined Radio, the CRs sense the radio frequency environment, selects the communication parameters such as carrier frequency, bandwidth and transmission power to optimize the spectrum usage and adapts its transmission and reception accordingly.

One of most critical components of cognitive radio technology is spectrum sensing. By sensing and adapting to the environment, a cognitive radio is able to fill in spectrum holes and serve its users without causing harmful interference to the licensed user. To do so, the cognitive radio must continuously sense the spectrum it is using in order to detect the re-appearance of the primary user. Once the primary user is detected, the cognitive radio should withdraw from the spectrum instantly to minimize the interference. This is complicated by the fact that primary users will be employing different modulation schemes, data rates and transmission powers in the presence of variable propagation environments.

1.2 Problem Statement

Another great challenge of implementing spectrum sensing, which will be our main focus, is the hidden terminal problem, which occurs when the cognitive radio is in severe multipath fading or inside buildings with high penetration loss while a primary user is operating in the vicinity. This can be solved by multiple cognitive users cooperating to conduct spectrum sensing.

The basic idea behind cooperative transmission rests on the observation that in a wireless environment, the signal transmitted or broadcast by a source to a destination node, each employing a single antenna, is also received by other terminals, which are often referred to as relays or partners. The relays process and retransmit the signals they receive. The destination node then combines the signals coming from the source and the partners, thereby creating spatial diversity and taking advantage of the multiple receptions of the same data at the various terminals and transmission paths. In addition, the interference among terminals can be dramatically suppressed by distributed spatial processing technology. Another more challenging problem to cooperative spectrum sensing is when reporting channels from cognitive radios to the common receiver are normally subject to fading.

Assumptions

Both sensing channels and reporting channels are simulated as flat Rayleigh fading. The SNR of the sensing channels and the reporting channels are taken as 10 and 25 dB, respectively. Energy detection is used for local spectrum sensing at each cognitive radio and the decision fusion is employed for reporting the sensing results to the common receiver.

Notation

H0	Primary user is absent
H1	Primary user is in operation
Di	*Energy Detection Reading at the ith cognitive Radio*
λ	*Energy threshold*
$R_x(\tau)$	cyclic autocorrelation function
E[]	the statistical expectation operation
α	*cyclic frequency*
S(f, α)	*Spectral Correlation Function*
Qf	*The probability of false alarm of cooperative spectrum sensing*
Qm	*The probability of miss of cooperative spectrum sensing*
Pd,i	*The correct decision probability of the local spectrum sensing of the ith cognitive radio*
Pf,i	*The false alarm probability of the local spectrum sensing of the ith cognitive radio*
Pm,i	*The miss probability of the local spectrum sensing of the ith cognitive radio*
$P_{e,i}$	*The probability of reporting errors of the ith cognitive radio*
W	Bandwidth
T	Observation Time Window
χ^2_{2u}	a central chi-square distribution with 2u degrees of freedom
$\chi^2_{2u}(2\gamma i)$	a non-central chi-square distribution with 2u degrees of freedom and a non-centrality parameter 2γi
γi	the instantaneous SNR of the received signal at the ith cognitive radio
u	u=TW
$H0^{BS,K}$	the decision *H*0 received from the *i*th cognitive radio at the BS for $i = 1, \cdots, K$.
$E\gamma i\,[\cdot]$	the expectation over the random variable *γi*
$\Gamma(\cdot, \cdot)$	the incomplete gamma function
$\Gamma(\cdot)$	the gamma function
h_i	the complex channel gain of the sensing channel between the primary user and the *i*th cognitive radio
$x(t)$	the observed signal at the *i*th cognitive radio
s(t)	the signal transmitted from the primary user
$n_i(t)$	the additive white Gaussian noise (AWGN)
K	Sensitivity Diversity Gain

2 Technical Background

Spectrum Sensing

Spectrum sensing is a key element in cognitive radio communications, as it should be performed before allowing unlicensed users to access a vacant licensed channel or vacating a recently occupied channel. The essence of spectrum sensing is a binary hypothesis-testing problem:

$H0$: Primary user is absent.
$H1$: Primary user is in operation.

The key metric in spectrum sensing are the probability of correct detection, probability of false alarm and probability of miss, which are given by respectively,

$Pd = \text{Prob}\ \{\text{Decision} = H1|H1\}$
$Pf = \text{Prob}\ \{\text{Decision} = H1|H0\}$
$Pm = \text{Prob}\ \{\text{Decision} = H0|H1\}$

Spectrum Sensing Techniques

To enhance the detection probability, many signal detection techniques can be used in spectrum sensing. Below are some of those techniques:

Energy Detection

The energy detection method is optimal for detecting any unknown zero-mean constellation signals. The radio frequency energy in the channel is measured to determine whether the channel is occupied or not. The received signals $x(t)$ sampled in a time window are first passed through an FFT device to get the spectrum $X(f)$.

The peak of the spectrum is then located. After windowing the peak in the spectrum of $x(t)$, we get $Y(f)$. The signal energy is then collected in the frequency domain. Finally, the following binary decision is made,

H1, if $\Sigma| Y (f) |^2 \geq \lambda$
H0, if $\Sigma| Y (f) |^2 < \lambda$

Advantages

It can be implemented without any prior knowledge of the primary user signal.

Disadvantages

It can only detect the signal of the primary user if the detected energy is above a threshold.
It cannot distinguish between secondary users sharing the same channel and the primary user.
The threshold selection for energy detection is difficult since it is highly susceptible to the changing background noise and interference level.

Matched Filter

A matched filter is obtained by correlating a known signal, or template, with an unknown signal to detect the presence of the template in the unknown signal. This is equivalent to convolving the unknown signal with a time-reversed version of the template.

Advantages

A matched filter is an optimal detection method as it maximizes the signal-to-noise ratio (SNR) of the received signal in the presence of additive Gaussian noise.

If partial information of primary user signal such as pilots or preambles is known, the use of matched filter is still possible for coherent detection

Disadvantages

The information of the primary user signal is hardly available at the cognitive radios.

Cyclostationary Detection

A signal is said to be cyclostationary (in the wide sense) if its autocorrelation is a periodic function of time t with some period. The cyclostationary detection can be performed as follows [15]. Firstly, one can calculate the cyclic autocorrelation function (CAF) of the observed signal $x(t)$, $R_x(\tau)$, as

$$R_x(\tau) = E[x(t + \tau)\, x^*(t - \tau)\, e^{-j2\pi\alpha t}]$$

where $E[\cdot]$ denotes the statistical expectation operation and α is called *cyclic frequency*. The discrete Fourier transformation of the CAF can then be computed to obtain the spectral correlation function (SCF), $S(f,\alpha)$, also called cyclic spectrum, which is a two-dimensional function in terms of frequency and cyclic frequency. Finally, the detection is completed by searching for the *unique cyclic frequency* corresponding to the peak in the SCF plane. The fact that the noise has only a peak of SCF at the zero cyclic frequency and the different modulated signals have different unique cyclic frequencies helps in detecting the existence of the primary user in the channel.

Advantages

If the signal of the primary user exhibits strong cyclostationary properties, it can be detected at very low SNR values.

This detection approach is robust to random noise and interference from other modulated signals

Disadvantages

It requires partial information from the primary user.

It requires high computational cost.

Wavelet Detection

In order to identify the locations of vacant frequency bands, the entire wideband is modeled as a train of consecutive frequency sub-bands where the power spectral characteristic is smooth within each sub-band but changes abruptly on the border of two neighboring sub-bands. By employing a wavelet transform of the power spectral density (PSD) of the observed signal $x(t)$, the singularities of the PSD $S(f)$ can be located and thus the vacant frequency bands can be found.

Advantages
For signal detection over wideband channels, the wavelet approach offers advantages in terms of both implementation cost and flexibility in adapting to the dynamic spectrum as opposed to conventional use of multiple narrowband bandpass filters (BPF)

Disadvantages
It requires high sampling rates for characterizing the large bandwidth.
It does not work for spread spectrum.
It requires high computational cost.

Performance of Spectrum Sensing

As mentioned above, the optimal detector for detecting a weak unknown signal from a known zero-mean constellation is the energy detector. The energy detection is performed by measuring the energy of the received signal in a fixed bandwidth W over an observation time window T. We assume that each cognitive radio performs local spectrum sensing independently. For simplicity, we consider the ith cognitive radio ($1 \leq i \leq K$) only to see how the energy detector works. The local spectrum sensing is to decide between the following two hypotheses,

$x_i(t) = n_i(t), H0$
$h_i{*}s(t) + n_i(t), H1$

As mentioned before, the energy collected in the frequency domain is $\mathrm{Di} = \sum |Y(f)|^2$ which serves as a decision statistic with the following distribution
Di χ^2_{2u} , H0
$\chi^2_{2u}(2\gamma i)$, H1

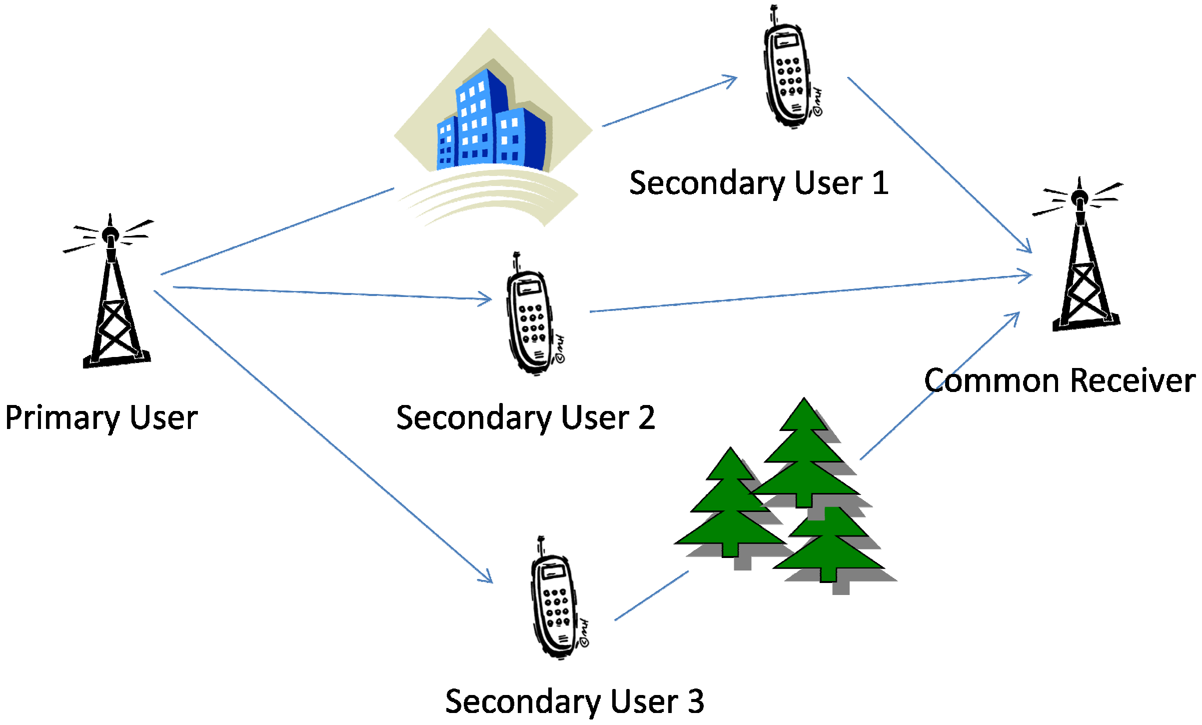
For the ith cognitive radio with the energy detector, the average probability of false alarm, the average probability of detection, and the average probability of miss over Rayleigh fading channels are given by, respectively,

$P\mathrm{f},i = \mathbf{E}\gamma i\,[\mathrm{Prob}\{Di > \lambda|H0\}]$
$= \Gamma(u, \lambda i/2)/\Gamma(u)$
$P\mathrm{d},i = \mathbf{E}\gamma i\,[\mathrm{Prob}\{Di > \lambda|H1\}]$
$P\mathrm{m},i = 1 - P\mathrm{d},i$

As a result of this, the energy detection performance of one cognitive radio becomes worse when SNR decreases when comparing Pm vs. Pf.

3 Body of Work
Cooperative Spectrum Sensing

One of the most critical issues of spectrum sensing is the hidden terminal problem, which happens when the cognitive radio is shadowed. As shown in the figure below, cognitive radio 1 is shown to be shadowed by a high building over the sensing channel. In this case, the cognitive radio cannot reliably sense the presence of the primary user due to the very low SNR of the received signal. Then, this cognitive radio assumes that the observed channel is vacant and begins to access this channel while the primary user is still in operation.



To address this issue, multiple cognitive radios can be coordinated to performance spectrum sensing cooperatively.

In general, cooperative spectrum sensing is performed as follows:

Algorithm A: Decision Fusion
- *Step 1*: Every cognitive radio performs local spectrum measurements independently and then makes a binary decision.
- *Step 2*: All the cognitive radios forward their binary decisions to a common receiver.
- *Step 3*: The common receiver combines those binary decisions and makes a final decision by fusing them to an “OR” logic to infer the absence or presence of the primary user in the observed band.

Advantages:
Low bandwidth in transmitting report (only one bit)

Algorithm B: Data Fusion

- *Step 1*: Every cognitive radio performs local spectrum measurements independently.
- *Step 2*: All the cognitive radios forward their observation values to a common receiver.
- *Step 3*: The common receiver combines those observation values and makes a final decision to infer the absence or presence of the primary user in the observed band.

Cooperative Spectrum Sensing Performance

In cooperative spectrum sensing, all cognitive radios measure the licensed spectrum and make the decisions independently. If the decision in one cognitive radio is H0, then a symbol $\{-1\}$ will be transmitted to the BS. If H1 is true, then $\{1\}$ is forwarded to the BS. The BS collects all K decisions and makes the final decision using an OR rule. Let Z denote the decision statistic in the BS, then it can be described as

$$Z \sim \begin{array}{ll} \{H0^{\mathrm{BS},\,10}, \ldots, H0^{\mathrm{BS},K}\}, & H0 \\ \text{Otherwise}, & H1 \end{array}$$

The BS decides the signal is absent only if all cognitive radios decide the absence of the signal. On the other hand, the BS assumes that the primary user is present if there exists at least one cognitive radio which assumes the presence of the primary user signal. Therefore, the false alarm probability of the cooperative spectrum sensing is given by

$$\begin{aligned} Q\mathrm{f} &= \mathrm{Prob}\{H1|H0\} \\ &= 1 - \mathrm{Prob}\{H0|H0\} \\ &= 1 - \prod_{i=1}^{K}(1 - P\mathrm{f},i) \end{aligned}$$

where Pf,i denotes the false alarm probability of the ith cognitive radio in its local spectrum sensing. The miss probability of cooperative spectrum sensing is given by

$$\begin{aligned} Qm &= \mathrm{Prob}\{H0|H1\} \\ &= \prod_{i=1}^{K} P\mathrm{m},i \end{aligned}$$

where $P\mathrm{m},i$ denotes the miss probability of the ith cognitive radio in its local spectrum sensing. Assume that every cognitive radio achieves the same $P\mathrm{f}$ and $P\mathrm{m}$ in the local spectrum sensing, the false alarm probability and the miss probability of cooperative spectrum sensing over Rayleigh fading channels are then given by

$$\begin{aligned} Q\mathrm{f} &= 1 - (1 - P\mathrm{f})^{K} \\ Q\mathrm{m} &= (P\mathrm{m})^{K}. \end{aligned}$$

It is obvious that the probability of miss is greatly reduced with a larger value K for a given probability of false alarm. As such, we may refer to K as the *sensing diversity gain* of the cooperative spectrum sensing.

It can be seen that cooperative spectrum sensing will go through two successive channels:
(1) *sensing channel* from the primary user to cognitive radios
(2) *reporting channel* from the cognitive radios to the common receiver.

Even though one cognitive radio may fail to detect the signal of the primary user, there are still many chances for other cognitive radios to detect it. With the increase of the number of cooperative cognitive radios, the probability of missed detection for all the users will be extremely small.

In practice, the reporting channels between the cognitive radios and the common receiver will also experience fading and shadowing. This will typically deteriorate the transmission reliability of the sensing results reported from the cognitive radios to the common receiver. Eventually, the performance of cooperative spectrum sensing will be degraded by the imperfect reporting channels.

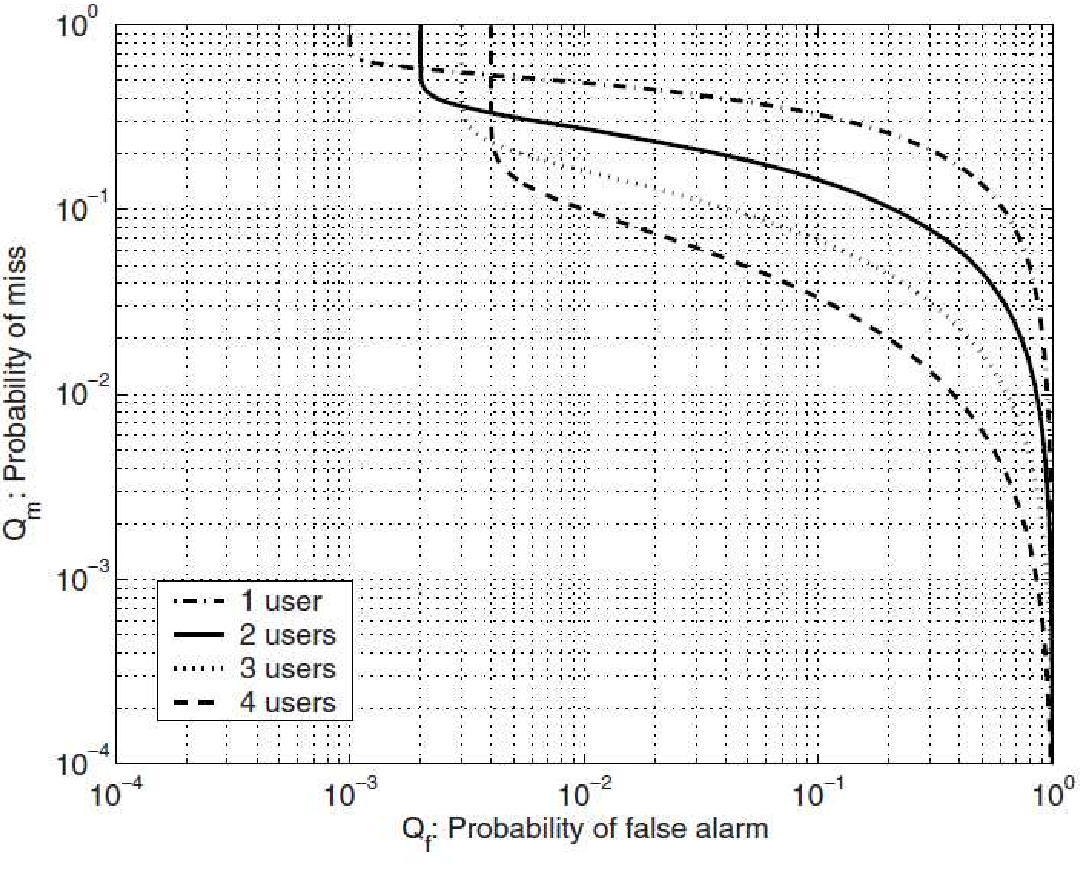
$Q\mathrm{f} = 1-\prod_{i=1}^{K} [(1 - Pf,i)(1 - Pe,i) + Pf,iPe,i]$
$Q\mathrm{m} = \prod_{i=1}^{K}[Pm,i(1 - Pe,i) + (1 - Pm,i)Pe,i]$

Suppose that the local spectrum sensing conducted by cognitive radio i results in $Pf,i = P\mathrm{f}$ *and* $Pm,i = P\mathrm{m}$, *for all* $i = 1, \cdots ,K$, *and that the probabilities of reporting errors are identical for all cognitive radios, then*

$Q\mathrm{f} = 1- [(1 - P\mathrm{f})(1 - Pe) + P\mathrm{f}Pe]^K$
$Q\mathrm{m} = [P\mathrm{m}(1 - Pe) + (1 - P\mathrm{m})Pe]^K$.

Furthermore, $Q\mathrm{f}$ *is bounded by*
$Q\mathrm{f} \geq Q\mathrm{f}^* = \lim_{Pf\to 0} Q\mathrm{f} = 1- (1 - Pe)^K \approx KPe.$

The figure below shows the ROC curves (probability of miss, $Q\mathrm{m}$ versus probability of false alarm, $Q\mathrm{f}$) of cooperative spectrum sensing under imperfect reporting scenarios for different number of cognitive radios. When the number of cognitive radios increases, the miss probability becomes smaller for any given false alarm probability.



However, it can be seen in the figure that each curve is chopped by a vertical line, which is called the *false alarm wall*, denoted by Qf^*. This implies that the false alarm probability cannot be sufficiently small due to the bound. It can be seen that the false alarm wall Qf^* becomes higher when the number of cognitive radios increases. Therefore, for the case that the desired false alarm probability is smaller than Qf^*, cooperative spectrum sensing will be completely invalid.

Cooperative Spectrum Sensing Techniques

Realistic Reporting channel degrade the performance of cooperative spectrum sensing. This can be solved by any of the technique presented below:

Cooperative Diversity for Cooperative spectrum Sensing

Multiple antennas technology has been shown as an efficient way to provide superior reception performance due to the potential high-space diversity. In cognitive radio networks, implementing multiple antennas at each cognitive radio is not practical due to the increasing cost and hardware complexity. However, a virtual antenna array can be formed by allowing multiple cognitive radios to cooperate.

For example, two cognitive users close to each other with an ideal channel between them can cooperate in spectrum sensing. After performing local spectrum sensing independently, the radios exchange their decisions and each one sends both decisions to the common receiver. Each decision is reported to the common receiver through two independent fading channels. This gives rise to a space diversity gain of 2. When the number of cognitive radios in cooperative spectrum sensing is K, it can be expected that a diversity gain of K will be achieved. Therefore, by exploiting a cooperative diversity among co-located cognitive radios, we can reduce the reporting error probability and then enhance the cooperative spectrum sensing performance.

Relay diversity for Cooperative spectrum Sensing

When the reporting channels of some cognitive radios experience heavy fading, the local decisions in these cognitive radios cannot be forwarded to the BS. This will reduce the cooperative diversity gain. If not all cognitive radios report to the common receiver, the common receiver will have to make a random decision on behalf of that cognitive radio. This will not improve the probability of detection. This can be solved by not counting unreliable reporting channels with low SNRs. However, the unreliable one can relay its local spectrum sensing result to other cognitive radios which are in enough good channel state.

This will increase the diversity gain of the cooperative spectrum sensing from $(K - M)$ to K where M is the number of faded cognitive radios. Just like cooperative a bound on Qf will also increase with an increase in the number of cooperative cognitive radios.

We employ channel coding to decrease the bound Qf while maintaining the maximum cooperative diversity. Assume that cognitive radio i experiences heavy shadowing and cognitive radio j experiences Rayleigh fading. In order to achieve the maximum cooperative diversity, cognitive radio i will relay its decision Xi to cognitive radio j. Then, the two decisions Xi and Xj which are BPSK symbols are encoded as
[Ci Cj]T = $\mathbf{\Theta}$[Xi Xj]T where $\mathbf{\Theta}$ is a 2×2 rotation matrix. Subsequently, Ci and Cj are sent through orthogonal channels $Hj(mi)$ and $Hj(mj)$, respectively. At the common receiver, the received symbols will be jointly decoded and then forwarded to perform a joint decision.

Multiuser diversity for Cooperative spectrum Sensing

Multiuser diversity is done by choosing the user with the highest SNR as the only physical transmission link between a cluster of radios and the common receiver. The SNR of the reporting channels between the cognitive radios and the common receiver are varied and are also independently changing due to the independent fading.

For example, all cognitive radios are configured into few clusters according to some distributed clustering method. Then, a cluster head is chosen in each cluster according to the highest SNR of the reporting channels. Once every cognitive radio in the same cluster finishes the local spectrum sensing, the sensing results will be reported to the cluster head which will then make a preliminary cooperative decision according to an “OR” logic rule. In the second layer, only cluster heads are required to report to the common receiver with their preliminary cooperative decisions and based on these decisions, the common receiver will make a final decision according to an “OR” logic rule.

Advantages:
The highest SNR is chosen as the cluster head to report the decisions to the common receiver thus reducing the reporting error probability.
The total amount of sensing bits reported to the common receiver can be greatly reduced thus lower false alarm wall.

Censored Decision for Cooperative spectrum Sensing

As the number of cognitive radios increase, the number of sensing bits increase which will also increase the sensing time. Decision are made based on comparison of the local sensing with a threshold, the readings close to the detection threshold are not reliable enough due to the noise disturbance. We eliminate the unreliable region close to the threshold by carefully setting the interval $[\lambda 1, \lambda 2]$. The cognitive radios having the readings out of this region are required to report to the common receiver. Specifically, the cognitive radio will report a local decision D:

$$D = 0,\ 0 \le O \le \lambda 1$$
$$\quad 1,\ O \ge \lambda 2.$$

But if $\lambda 1 < O < \lambda 2$, the cognitive radio will not report anything to the common receiver. The probability of the event that one cognitive radio participates in the reporting process can be calculated by
$K^* = 1 - \mathrm{Prob}\{\lambda 1 < O < \lambda 2\}$

The average transmitted sensing bits will be greatly reduced without much affecting the sensing performance much. This is because those unreliable decisions are censored and excluded from the final decision. Employing half of total number of cognitive radios for cooperative spectrum sensing will not necessarily lead to the loss of performance. This is because the other half of total number of cognitive radios has a local decision in ambiguous region, which will be much unreliable and cannot improve the sensing performance.

Asynchronous Cooperative spectrum Sensing

All the schemes mentioned above need to set an enough long observation time beforehand to ensure every sensing node can conduct the spectrum sensing accurately. Taking into account the sensing ability diversity of the sensing nodes with different SNR, in which the cognitive radio with high SNR finishes the detection and sends the result to center earlier than the one with low SNR, and the center node makes a final decision using the “OR” rule depending on the first local decision without waiting for the other local decisions, thus to reduce the sensing time and improve the agility of spectrum sensing.

Advantages:
Faster detection Time

Disadvantages:
Loss of reliability of measure
Reduction in the possibility of detection

4 Conclusion & Future Research

4.1 Conclusions

Cognitive radio is an agile radio technology that can efficiently utilize the spectrum holes of the licensed channels in different locations and times. To detect the spectrum holes accurately and quickly, spectrum sensing is a critical component in cognitive radio systems. A compilation of spectrum sensing techniques for cognitive radios has been presented. The conventional spectrum sensing methods have firstly been introduced and their advantages and disadvantages have been discussed. In order to deal with the hidden terminal problem, which is commonly seen in wireless networks, cooperative spectrum sensing has been considered. By allowing a number of cognitive radios to perform local spectrum sensing independently and fusing their local decision results together at common receiver, the spectrum sensing performance is greatly enhanced. Cooperative spectrum sensing has also been considered for realistic fading scenarios, where both the sensing channels and reporting channels are subject to fading and/or shadowing. Performance analysis of cooperative spectrum sensing under realistic fading channels has been given and a limitation of the cooperative spectrum sensing has been observed. To address this and other cooperative spectrum sensing challenges, several robust cooperative spectrum-sensing techniques have been proposed. Further research on cooperative spectrum sensing can be envisioned on wideband sensing.

4.2 Future Research

As further research in this subject, MATLAB or LABVIEW simulations will run to compare the effectiveness of these techniques. Also, these simulations will then be compared to real-life situations of cognitive radios.

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