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A Random Censoring Scheme for Cooperative Spectrum Sensing

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Abstract—In this paper, we develop a new scheme to effectively detect the primary signal in a cognitive radio (CR) network. We propose a packet transmission scheme with random censoring. The proposed scheme, known as Censored with Probability Fusion Method (CPFM), controls the information exchange in cooperative spectrum sensing so as to improve the detection performance and reduce the cooperation overheads. In CPFM, each participating CR device independently senses the spectrum. Based on the energy level received, it may transmit, not transmit, or randomly transmit its observation packet to the fusion centre. The fusion centre then determines the spectrum condition based on all packets received. The simulation results show that CPFM outperforms other detection schemes in terms of improved detection probability and smaller control overheads.

I. INTRODUCTION

Cognitive Radio (CR) technology [7] provides a convenient and cost-effective solution for the spectrum shortage problem. Channels are licensed to primary users, which may not always occupy such channels. By making use of the temporarily idle licensed channels, secondary users, which must not interfere with the transmission of primary users, can help increase the usage of the channel bandwidth [11]. Such secondary users are also known as CR users in this paper. The success of CR depends on the ability of the system to detect, access, and manage idle channels.

To improve the detection probability (i.e. detection accuracy about the transmission activities of primary users), different techniques have been devised. In addition to improving individual sensing capability, recent approaches rely on cooperative spectrum sensing. Cooperative spectrum sensing is a sensing technique that exploits the spatial diversity of a CR network by primary signal detection. It requires CR devices to send their observation results to a centralized fusion centre, which makes a spectrum decision based on such results. In the hard combination censored scheme [3], [12], nodes send the observation packets to the fusion centre only when they detect the presence of the primary signals, and the spectrum is considered busy if the fusion centre receives any observation packets. This scheme does not require large control overheads since the CR users would be censored if the received signal is weak. Although this method can statistically improve the detection probability, it also increases the false alarm probability (when the fusion centre indicates the channel to be busy while it is not), thereby reducing the spectrum efficiency. A relatively softer scheme, such as the 2-bit combination scheme in [5], requires nodes to assign their decisions with certain weights corresponding to their received energy levels when sending the observation results to the fusion centre. The fusion centre sums up the weights and declares the channel to be busy when the sum is larger than a given threshold. These methods apply the idea of the weighted sum similar to the optimal scheme using the Neyman-Pearson hypothesis testing model [12]. Hence, they significantly improve the detection probability and reduce the false alarm probability. However, these schemes also require a relatively large bandwidth for observation packet transmissions. This may become a burden to a CR network.

Cooperative spectrum sensing can help improve the detection performance by exploiting spatial diversity so as to cope with the hidden terminal, multipath fading, and shadowing problem. However, it also incurs more control overheads. Therefore, the objective of this paper is to develop a scheme that can strike a balance between the detection performance and the control overheads.

A. Our Contributions

The focus of this work is to devise a random censoring fusion mechanism, known as Censored with Probability Fusion Method (CPFM). The proposed scheme not only yields a high detection probability by cooperative spectrum sensing, but also incurs relatively small control overheads by selective transmission of the observation packets to the fusion centre.

B. Organization of the Paper

The paper is organized as follows. Section II gives the system model of cooperative signal detection in a CR network. Section III presents and analyzes our proposed Censored with Probability Fusion Method (CPFM). Section IV presents the simulation results and compares the performance of CPFM with other existing techniques. Section V concludes and discusses the merit of CPFM.

II. SYSTEM MODEL

Cooperation detection is a spectrum sensing method where information from multiple CR users is incorporated for detecting the transmission activities of the primary users. To perform spectrum detection, a CR user senses the energy level of the specific spectrum by taking several samples in a sensing period. In order to perform cooperative sensing, the CR user sends its observation packet to the centralized fusion centre. The fusion centre analyzes the received information so as to decide whether primary users are currently transmitting. The decision is finally broadcasted to all CR users within the cluster. The users record this decision and avoid accessing the busy channel for data transmission.

The scope of this section is to develop a simple model of a CR network. This model is then used to analyze the performance of
the proposed cooperative sensing scheme. Here, we make some assumptions to simplify the analysis.

A. Transmitted Signal

We consider $N$ CR users in a network for cooperative sensing. For every detection period, $M$ spectrum samples are taken within $T$ seconds. The $m$th received sample of the $n$th CR user (where $m = 1, 2, ..., M$ and $n = 1, 2, ..., N$) can be represented [9] as:

$$
 r_{nm} = \left\{ \begin{array}{ll}
 n_{nm} \sqrt{r_n s_{nm}} + n_{nm} & H_0 \\
 H_1 & H_1 
 \end{array} \right. $$

where the hypotheses $H_0$ and $H_1$ correspond to the absence and presence of the primary signal (i.e. the signal from a primary user), respectively. $n_{nm}$ denotes white noise, which is assumed to be independent, identically and normally distributed. $r_n$ represents the average signal–to–noise–ratio (SNR) of the received primary signal. $\sqrt{r_n s_{nm}}$ denotes the received primary signal. Here, we assume $s_{nm}$ to be independent and identically distributed since the received signal can be regarded as a superposition of several independent non–line–of–sight signals [5]. Therefore, $r_{nm}$ follows a normal distribution, which can be expressed as:

$$
 r_{nm} \sim \left\{ \begin{array}{ll}
 \mathbb{N}(0, 1) & H_0 \\
 \mathbb{N}(0, 1 + r_n) & H_1 
 \end{array} \right. $$

B. Local Energy Level

By signal sampling, the detected energy level can be expressed [5] as:

$$
 Y_n = \sum_{m=1}^{M} r_{nm} = \left\{ \begin{array}{ll}
 b_{1n} & H_0 \\
 (1 + r_n)b_{2n} & H_1 
 \end{array} \right. $$

where $b_{1n}$ and $b_{2n}$ are independent random variables following a central chi-square distribution with $M$ degrees of freedom, where $n = 1, 2, ..., N$.

C. Channel Condition

The primary signal may experience channel fading before being received by the CR users. In this paper, we assume that the primary signal experiences independent Nakagami fading. The probability density function of the received signal power $r$ is given [2] by:

$$
 f_{\text{Nak}}(r) = \frac{1}{\Gamma(m)} \left( \frac{m}{\tau} \right)^m r^{m-1} e^{-\frac{mr}{\tau}} \quad r \geq 0
$$

where $m$ is the Nakagami parameter and $\tau$ is the SNR of the transmitted primary signal. When $m = 1$, it becomes Rayleigh fading. The signal fluctuation is reduced when $m > 1$.

III. CENSORED WITH PROBABILITY FUSION METHOD

In this section, we present our proposed cooperative sensing scheme, known as Censored with Probability Fusion Method (CPFM). The discussion will proceed as follows. Section III-A gives the motivation of the scheme. Section III-B presents the procedure of CPFM, which is analyzed in Section III-C.

A. Motivation

Fig. 1 shows the probability density function (p.d.f.) of $Y_n$, under various settings on the average SNR of the received primary signal.

B. Algorithm

Motivated by the idea of censoring [3], [8], [10], and soft combination [5], [9], and the discussion in Section III-A, we propose a cooperative scheme known as CPFM. The philosophy of CPFM is to control the rate at which observation packets are sent to the fusion centre. The transmission probability of an observation packet is higher when the observation information is more useful, and vice versa. This helps reduce the cooperation overheads while maintaining the detection performance.

However, in practice, the primary signal strength of the primary transmitter is unknown. This makes it hard to determine the p.d.f. of the detected energy level. In CPFM, we use the last reported observed energy level, $Y_n'$, as the centre of the expected range. The assumption behind this choice is that the detected energy level would not change much if the status of the primary signal remains unchanged. Using $Y_n'$ as the reference, the whole range of the detected energy level can be divided into three regions, namely, Expected (E), NotSure (NS), and UnExpected (UE), as shown in Fig. 2.
C. Analysis

In this subsection, we analyze the performance of CPFM in cooperative spectrum sensing. We derive the expression for information fusion in CPFM and the false alarm probability, transmission probability, and response time. First, we need to make several assumptions about the network:

1) The transmission of any observation packet to the fusion centre is error-free.

2) The statistical properties of all channel conditions are unchanged. This means that the status of the primary signal remains unchanged, and $Y_n$ and $Y_n'$ follow the same statistical distributions.

The CPFM scheme applies the Neyman-Pearson hypothesis testing model [12] for combining the observation results so as to maximize the detection probability with a fixed false alarm probability. This method is also used in the optimal soft combining scheme. In CPFM, the CR users send their detected energy levels to the fusion centre without any pre-processing. The fusion centre then makes use of the received information from all nodes and decides whether the primary signal is present. By [12], the likelihood ratio test can be expressed as:

$$L(y) = \prod_{n=1}^{N} \frac{f_{Y_n}(y_n|H_1)}{f_{Y_n}(y_n|H_0)} \geq \frac{H_0}{H_1} \lambda$$ (5)

where $N$ is the number of CR users participating in the cooperative sensing, $y_n$ is the energy level detected by User $n$, and $y = (y_1, y_2, \ldots, y_N)$. $\lambda$ is the optimal threshold for maximizing the detection probability with a given false alarm probability, and $f_{Y_n}(y_n|H_1)$ and $f_{Y_n}(y_n|H_0)$ are the conditional p.d.f. of $Y_n$ given the presence and absence of the primary signal, respectively.

According to (3), $Y_n$ follows a chi-square distribution with $M$ degrees of freedom. $f_{Y_n}(y_n|H_0)$ and $f_{Y_n}(y_n|H_1)$ can be expressed [5] as:

$$f_{Y_n}(y_n|H_0) = \begin{cases} \frac{\lambda^{y_n/2}}{2^{y_n/2} \Gamma(y_n/2)} & y_n \geq 0 \\ 0 & y_n < 0 \end{cases}$$ (6)

and

$$f_{Y_n}(y_n|H_1) = \begin{cases} \frac{\lambda^{y_n/2}}{2^{y_n/2} \Gamma(y_n/2)(1+r_n)} & y_n \geq 0 \\ 0 & y_n < 0 \end{cases}$$ (7)

where $\Gamma(\cdot)$ denotes the gamma function.

By (5) - (7) and taking logarithm on both sides, the likelihood ratio test becomes [12]:

$$L'(y) = \sum_{n=1}^{N} \frac{r_n}{1+r_n} y_n = \lambda' \geq \frac{H_1}{H_0} 2 \ln \lambda + M \sum_{n=1}^{N} (1+r_n)$$ (8)

$L'$ is the weighted sum of $y_n$ and the weight $\frac{r_n}{1+r_n}$ is related to the SNR of the received primary signal $r_n$.

Under $H_0$, $L'$ becomes the equal weighted sum of $y_n$. Thus, $L'$ follows an independent and identically distributed central chi-squared distribution with $MN$ degrees of freedoms. By (6), the false alarm probability can be expressed as [2]:

$$P_f = \frac{\Gamma(MN/2, \lambda'/2)}{\Gamma(MN/2)}$$ (9)

where $\Gamma(\cdot, \cdot)$ denotes the upper incomplete gamma function.

By fixing $P_f$, the threshold $\lambda'$ can be calculated using (9). Lowering the thresholds makes the network more sensitive in detecting the primary signals. However, the CR network becomes more vulnerable to noise, leading to increase in the false alarm probability.

Given that $H_0$ holds, the received signal is noise. According to (3), $Y_n$ follows a central chi-square distribution with $M$ degrees of freedom.

For CPFM, the conditional probability of packet transmission
of a CR user with $Y_n' = y_n'$ can be achieved by (6):

$$P_n(\text{send}|y_n', H_0) = 1 - (1 - p_s) \int_{y_n' - \delta}^{y_n' + \delta} f_{Y_n}(y_n|H_0)dy_n - p_s \int_{y_n' - \sigma}^{y_n' + \sigma} f_{Y_n}(y_n|H_0)dy_n$$

By (6) and (10), the average conditional probability for packet transmission of CR users under $H_0$ can be calculated as:

$$P(\text{tran}|H_0) = \frac{1}{N} \sum_{n=1}^{N} \int_{0}^{\infty} f_{Y_n}(y_n'|H_0)P_n(\text{send}|y_n', H_0)dy_n'$$

Given that $H_1$ holds, the received signal is both noise and the primary signal with channel fading. Here, by considering the effect of Nakagami channel fading and (4), (7) can be rewritten as:

$$f_{Y_n}(y_n|H_1) = \begin{cases} \int_{0}^{\infty} \frac{y_n^\mu e^{-\frac{y_n^2}{\Gamma(\frac{\mu}{2})}}}{2^{\frac{\mu}{2}}\Gamma(\frac{\mu}{2})} f_{N}(r_n)dr_n & y_n \geq 0 \\ 0 & y_n < 0 \end{cases}$$

By (12), the conditional probability of packet transmission of a CR user with $Y_n' = y_n'$ is:

$$P_n(\text{send}|y_n', H_1) = 1 - (1 - p_s) \int_{y_n' - \delta}^{y_n' + \delta} f_{Y_n}(y_n|H_1)dy_n + p_s \int_{y_n' - \sigma}^{y_n' + \sigma} f_{Y_n}(y_n|H_1)dy_n$$

Hence, by (12) and (13), the average conditional probability for packet transmission of CR users under $H_1$ can be calculated as:

$$P(\text{tran}|H_1) = \frac{1}{N} \sum_{n=1}^{N} \int_{0}^{\infty} f_{Y_n}(y_n'|H_1)P_n(\text{send}|y_n', H_1)dy_n'$$

When the channel status changes from busy to idle, the CR users might need a certain period to realize the change and refresh the observation information in the fusion centre. In this case, by (10) and (12), the conditional probability for a CR user sending a packet is:

$$P_n(\text{tran}|H_1 \rightarrow H_0) = \int_{0}^{\infty} f_{Y_n}(y_n'|H_1)P_n(\text{send}|y_n', H_0)dy_n'$$

Hence, the minimum sensing periods required for all CR users to update their observation with a 90% of confidence is:

$$L_{H_1 \rightarrow H_0}(0.9) = \left[ \frac{\ln 0.1}{\ln(1 - \prod_{n=1}^{N} P_n(\text{tran}|H_1 \rightarrow H_0))} \right]$$

When channel status changes from idle to busy, a certain period is also required for a CR user to refresh its observation information in the fusion centre. In this case, by (6) and (13), the probability for a CR user sending a packet is:

$$P_n(\text{tran}|H_0 \rightarrow H_1) = \int_{0}^{\infty} f_{Y_n}(y_n'|H_0)P_n(\text{send}|y_n', H_1)dy_n'$$

Hence, the minimum sensing periods required for all CR users to update their observation with a 90% of confidence is:

$$L_{H_0 \rightarrow H_1}(0.9) = \left[ \frac{\ln 0.1}{\ln(1 - \prod_{n=1}^{N} P_n(\text{tran}|H_0 \rightarrow H_1))} \right]$$

The response time $L_{H_0 \rightarrow H_1}(0.9)$ and $L_{H_1 \rightarrow H_0}(0.9)$ correspond to how quickly the CPFM network can respond to the channel status changes and their values are decided by the channel requirements for the cognitive radio network. Assuming that the channel is idle for most of the time, $P(\text{tran}|H_0)$ should be kept low enough to minimize the control overheads. Thus, by fixing $L_{H_0 \rightarrow H_1}(0.9)$ and $L_{H_1 \rightarrow H_0}(0.9)$ and minimizing $P(\text{tran}|H_0)$ with (11), (16), and (18), the value of $p_s$, $\delta$, and $\sigma$ can be numerically calculated.

IV. PERFORMANCE EVALUATION

In this section, we present the simulation results of our proposed scheme and compare it with three other cooperative sensing schemes: optimal soft combining scheme, hard combining scheme, and 2-bit hard combining scheme.

A. Simulation Setup

Our simulation experiments are based on a CR network where CR users perform cooperative sensing to detect the presence of the primary signal. We use Gaussian distributed streams as the primary signal and as noise. For simplicity, we assume that all CR users experience the same average channel SNR with the Rayleigh fading channel. In the CR network, four homogeneous CR devices are employed to observe the primary signal. During each sensing period, six samples are taken and the energy level is achieved by (3). These CR users then transmit the observation packets to the fusion centre following different cooperative schemes. The fusion centre analyzes the received packets and makes the final decision on the channel condition. Each simulation run consists of 21,000 sensing periods. The statistics for computing the detection performance and packet transmission rate are collected only when the first 1,000 cooperative sensings have been conducted. A total of 10 runs have been done to measure the detection performance and packet transmission rate.

B. Parameter Determination

Firstly, we determine the threshold $\lambda$ for CPFM by setting the false alarm probability to 0.01 and calculating the threshold using (9). Then, we determine the transmission probability $p_s$ and the values of $\delta$ and $\sigma$ using (11), (16), and (18). We set both $L_{H_0 \rightarrow H_1}(0.9)$ and $L_{H_1 \rightarrow H_0}(0.9)$ to be two (which means in 90% cases, the observation information of all CR users would be refreshed two sensing periods after a change in the channel status) and set the average SNR of the active channel to be 8 dB. By minimizing $P(\text{tran}|H_0)$ with $L_{H_0 \rightarrow H_1}(0.9)$ and $L_{H_1 \rightarrow H_0}(0.9)$ both equal to two, the optimal values of $p_s$, $\delta$, and $\sigma$ are numerically determined.
C. Detection Performance

With the false alarm probability equal to 0.01, we compare the detection performance of different cooperative schemes by measuring their normalized average detection probability with different primary signal SNR. As expected, both the optimal soft combining scheme and CPFM offer the best detection performance with the given false alarm probability due to the same fusion method they apply. The 2-bit combining scheme is a relatively “softer” scheme than the one-bit hard combining scheme due to the application of the weighting sum. However, the quantized weighting limits its improvement and thus the detection probability of the 2-bit combining scheme is less than CPFM.

D. Control Overheads

With the same false alarm probability, we compare the control overheads of different cooperative schemes by measuring the normalized packet transmission probability of a CR user with different primary signal SNR. We count the total number of times the CR user transmits its observation packets to the fusion centre and divide it by the total number of individual spectrum sensing as the average transmission rate of a CR user.

![Normalized average packet transmission rate against average primary signal SNR.](image)

Fig. 3 shows the normalized average packet transmission rate against the average primary signal SNR so as to compare the control overheads of the four schemes. The transmission probability of the soft combining scheme keeps constant at one packet per observation period. This suggests that a CR user needs to send one packet to the fusion centre every time it makes a channel detection. For the other three schemes, the packet transmission rate increases with the primary signal SNR. The packet transmission rate of the 2-bit scheme is larger than one-bit OR combining due to its low threshold for transmission. Based on the simulation results, we can infer that under current parameter settings, the control overhead of the CPFM scheme is comparable to the 2-bit scheme. The packet transmission rate of CPFM is a little bit higher than the 2-bit scheme in low SNR levels but falls below the 2-bit scheme when SNR is larger than -2 dB. In addition, the channel overheads of both CPFM and 2-bit scheme are a lot less than the optimal scheme.

V. CONCLUSIONS

In this paper, we introduce the concept of random censoring and propose the CPFM scheme for cooperation detection. By randomly censoring the transmission of less informative observation, CPFM can largely reduce the control overheads due to observation packet transmissions while significantly improving the detection performance.

We present the scenario of CR spectrum sensing and analyze the network properties and channel conditions. Motivated by the optimal scheme and energy level distribution in Fig. 1, we classify the observations into three regions and use random censoring to reduce or eliminate the transmissions of less useful observations.

Our result shows that CPFM reduces the packet transmission of CR users while keeping the same detection performance as in the optimal scheme. In addition, the parameters in CPFM can be adjusted with more relaxed channel requirement on response time to further reduce the channel overheads. Therefore, CPFM is effective for high quality cooperative detection in CR network with limited control channel bandwidth.

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