BANDWIDTH EFFICIENT COMBINATION FOR COOPERATIVE SPECTRUM SENSING IN COGNITIVE RADIO NETWORKS

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ABSTRACT

In this paper, we investigate bandwidth efficient combination of spectrum sensing information in cooperative cognitive radio (CR) networks. We propose a general approach in which CR users are allowed to simultaneously send local sensing data to a combining node through a common control channel, based on which we discuss bandwidth efficient combination schemes under two different cases. In the proposed schemes, the bandwidth required for reporting is fixed regardless of the number of cooperative users. With proper preprocessing at individual users, the proposed schemes maintain reasonable performance with the superposition of sensing data at the combining node. Simulation results also demonstrate the effectiveness of the proposed approach.

Index Terms— Bandwidth efficiency, cognitive radio, cooperative spectrum sensing, reporting latency

1. INTRODUCTION

As a potential solution to wireless spectrum scarcity issue, cognitive radio (CR) technology has been introduced to achieve much higher bandwidth efficiency by opportunistically utilizing licensed spectrum [1]. CR users are allowed to use the licensed spectrum bands only when they do not cause unacceptable interference with licensed users. Therefore, spectrum sensing [2], which monitors the usage of the licensed spectrum, is required before CR communications. However, spectrum sensing by a single CR user cannot ensure sufficient detection reliability because of fading and time varying nature of wireless channels. To mitigate these impacts, cooperative spectrum sensing [3] has been proposed by taking advantage of spatial diversity in multiuser CR networks.

In cooperative spectrum sensing, each CR user reports local sensing information to a combining node, which makes a decision on the presence or absence of the licensed signal. It is usually assumed in the literature that a common control channel is available for reporting regardless of the amount of individual sensing data. Bandwidth efficient combination methods for cooperative spectrum sensing with quantization have been investigated in [4]. Similar problems have also been studied in sensor networks to reduce communication bandwidth requirements [5]. However, as the number of cooperative users increases, the bandwidth required for reporting also increases in these schemes due to the fact that the sensing data from different CR users are transmitted through orthogonal channels, i.e., separated in different time slots, frequency bands, or codes. Therefore, the stringent bandwidth constraint of the common control channel may not be satisfied.

To address the above issue, we investigate bandwidth efficient combination for cooperative spectrum sensing in this paper. We allow sensing data from different CR users to be sent simultaneously through the same narrowband channel, which saves the required bandwidth, but results in the superposition of individual sensing data. Therefore, careful design of local information processing at the CR users and final decision rule at the combining node is necessary. We consider the optimal schemes when the reporting channel is Gaussian and experiences fading, respectively. With proper preprocessing at individual users, the proposed approach maintains reasonable performance with the superposition of sensing data.

The remainder of this paper is organized as follows. In Section 2, we briefly describe the system model of cooperative spectrum sensing in multiuser CR networks. In Sections 3 and 4, we develop the optimal bandwidth efficient combination schemes under two different cases. Then we further present simulation results in Section 5. Finally Section 6 concludes this paper.

2. SYSTEM MODEL

In this paper, we study cooperative spectrum sensing in a multiuser CR network consisting of $K$ CR users and a combining node. With local spectrum sensing, each CR user collects its observation, processes and reports to the combining node via a common control channel. Upon receiving the sensing data from different CR users, the combining node makes a decision on whether the licensed signal is present or not.

2.1. Local Spectrum Sensing and Processing

The $n$th sample of the $k$th CR user, $1 \leq n \leq N$, $1 \leq k \leq K$, is

$$r_{k,n} = \begin{cases} \tilde{w}_{k,n}, & \mathcal{H}_0, \\ \tilde{h}_{k,n} s_{k,n} + \tilde{w}_{k,n}, & \mathcal{H}_1, \end{cases}$$

where $\tilde{h}_{k,n}$ denotes the receive signal vector at the CR user, $\tilde{w}_{k,n}$ denotes the additive white Gaussian noise (AWGN) at the CR user, $\mathcal{H}_0$ and $\mathcal{H}_1$ denote the hypotheses corresponding to the absence and presence of the licensed signal, respectively. The received signal vector at the $k$th CR user can be denoted as $\mathbf{r}_k = [r_{k,1}, r_{k,2}, ..., r_{k,N}]^T$.

CR users are not required to make local decisions in cooperative spectrum sensing since the combining node will finally make a decision. Therefore, the goal of local spectrum sensing at each cooperative user is generally to provide the combining node some indication on the likelihood between the two hypotheses, $\mathcal{H}_0$ and $\mathcal{H}_1$, from the observation. Sending the received signal samples without
2.2. Combination for Cooperative Spectrum Sensing

In cooperative spectrum sensing, CR users report to the combining node through the common control channel. According to the sensing data collected from these users, the combining node decides between the two hypotheses in (1) based on its combining strategy. Figure 1 gives a general schematic representation for combination of sensing data in cooperative spectrum sensing. As shown in this figure, among the $K$ cooperative CR users, the $k$th CR user, $1 \leq k \leq K$, independently obtains the sensing data, $r_k$, and reports the processed data, $q_k$, to the combining node through the common control channel. Upon receiving the combined sensing data, $z$, from all the CR users, the combining node makes a decision, $d$, on the absence or presence of the licensed signal.

To separate the sensing data from different users, orthogonal channels, such as different time slots in time division multiple access (TDMA), frequency bands in frequency division multiple access (FDMA), and codes in code division multiple access (CDMA), are commonly used for reporting. Thus the received sensing data at the combining node can be expressed as

$$z = [h_1 q_1 + w_1, h_2 q_2 + w_2, ..., h_K q_K + w_K]^T,$$

where $h_k$ is the reporting channel gain between the $k$th CR user and the combining node as shown in Figure 1, and $w_k$ is the corresponding zero-mean AWGN at the combining node. The total channel use is of $O(K)$, which, as the number of cooperative CR users increases, may not satisfy the stringent bandwidth constraint of the common control channel in the CR environment.

In this paper, we focus on a novel approach that CR users simultaneously report the processed sensing data through the common control channel so that the combining node receives the superposition of all the data. Although such an approach is not preferred in general wireless communications, it intuitively works in cooperative spectrum sensing since the data from all the CR users are related to the same phenomenon, i.e., on the absence or presence of the licensed signal. In this case, the received sensing data at the combining node is

$$z = \sum_{k=1}^{K} h_k q_k + w,$$

where $w$ is the zero-mean AWGN at the combining node. It is obvious that this approach is much more bandwidth-efficient because only one unit of bandwidth resource is required for reporting the sensing data regardless of the number of cooperative users.

3. OPTIMAL DESIGN WITH GAUSSIAN REPORTING CHANNEL

When the reporting channel is Gaussian, (4) can be rewritten as

$$z = \sum_{k=1}^{K} q_k + w,$$

where we let $h_k = 1$ for $1 \leq k \leq K$ without loss of generality.

Before considering the optimal design of bandwidth efficient combination in this case, we first take a look at the situation if the combining node knows the received signal vectors at all the CR users. Under either Neyman-Pearson or Bayesian criterion, the optimal decision rule is given by [6] as

$$f(r_1, r_2, ..., r_K | H_1) \leq \frac{\eta_1}{\eta_0},$$

where $\eta$ is a threshold determined by the target overall detection performance.

Since different CR users independently obtain the sensing data, we further have

$$f(r_1, r_2, ..., r_K | H_i) = \prod_{k=1}^{K} f(r_k | H_i) \text{ for } i = 0, 1.$$

Enlightened by the above, if we design the local processing function as

$$q_k = Q_k(r_k) = \log \frac{f(r_k | H_1)}{f(r_k | H_0)},$$

where $q_k$ is a real-valued scalar, which will be sent by the $k$th CR user without quantization, the superposition of all the scalars, $\sum_{k=1}^{K} q_k$, will automatically become the logarithm of the test statistic in (6). Therefore, the global decision rule

$$d = \begin{cases} H_0, & z < \log \eta_1, \\ H_1, & z \geq \log \eta_1 \end{cases}$$

is obviously optimal if there is no noise term in (5). If the channel noise exists, the unquantized transmission of $q_k$ as expressed in (8) is still asymptotically optimal as has been proved in [7].

The problem remaining is how each CR user computes its processed sensing data with its observation, i.e., to calculate $f(r_k | H_i)$ given $r_k$. Without loss of generality, we allow reporting latencies and assume that the received signal vector of the $k$th CR user, $r_k$, is acquired at $t_k$ and the final combination is to be made at $t$. Thus $H_0$ and $H_1$ denote the hypotheses corresponding to the absence and presence of the licensed signal at the specific time $t$, respectively.

According to the Bayes’ theorem [8], $f(r_k | H_i)$ can be expressed as

$$f(r_k | H_i) = f(r_k | I_k)P(I_k | H_i) + f(r_k | B_k)P(B_k | H_i),$$

where

$$I_k$$

is the reporting channel gain between the $k$th CR user and the combining node, where $q_k$ is in general a vector but we will use the scalar version throughout the paper.
where $I_k$ and $B_k$ denote that the licensed signal is absent and present at $t_k$, respectively.

We can model the occupancy of the licensed spectrum band as a renewal process alternating between busy and idle states [8], which correspond to that the band is occupied and unoccupied by licensed users, respectively. As indicated by the measurement in [9], we assume the busy and idle periods to be exponentially distributed with probability density functions (PDFs) $f_B(t) = \alpha e^{-\alpha t}$ and $f_I(t) = \beta e^{-\beta t}$, respectively, where $\alpha$ is the transition rate from busy to idle state, and $\beta$ is the transition rate from idle to busy state. Therefore, the prior probabilities of the licensed spectrum band status can be obtained as $P_B = \frac{\beta}{\alpha + \beta}$ and $P_I = \frac{\alpha}{\alpha + \beta}$. With the help of age distribution of renewal process and memoryless property of exponential distribution, we have

$$P(B_k | \mathcal{H}_t) = \int_{t-t_k}^{\infty} f_B(\tau) d\tau = e^{-\alpha(t-t_k)} \quad (11)$$

and

$$P(I_k | \mathcal{H}_t) = \int_{t-t_k}^{\infty} f_I(\tau) d\tau = e^{-\beta(t-t_k)}. \quad (12)$$

Note that $P(B_k | \mathcal{H}_t) + P(I_k | \mathcal{H}_t) = 1$ for $i = 0, 1$. So $P(B_k | \mathcal{H}_0)$ and $P(I_k | \mathcal{H}_1)$ can be further obtained.

Without loss of generality, we assume that $s_{k,n}$ and $w_{k,n}$ are both Gaussian distributed with zero mean and unit variance. Given that the samples of any CR user are independent, the conditional PDFs $f(\mathbf{r}_k | I_k)$ and $f(\mathbf{r}_k | B_k)$ are [10]

$$f(\mathbf{r}_k | I_k) = \frac{1}{\sqrt{2\pi}} \exp \left( -\frac{\mathbf{r}_k^2}{2} \right) \quad (13)$$

and

$$f(\mathbf{r}_k | B_k) = \frac{1}{\sqrt{2\pi(1 + h_k^2)}} \exp \left( -\frac{\mathbf{r}_k^2}{2(1 + h_k^2)} \right). \quad (14)$$

With (10)–(14), we can further obtain the likelihood ratio in (8) and the hypothesis test can be applied with a final decision on whether the licensed signal is present or not.

### 4. OPTIMAL DESIGN WITH FAADING REPORTING CHANNEL

When the reporting channel experiences fading, the superposition of scalars in the above approach will no longer work as a proper test statistic, due to the random phases of individual channel paths. However, we may retain the bandwidth benefit with the superposition approach by modifying the local processing functions and relating the global decision rule to the received power.

Without loss of generality, we assume that the reporting channel between the $k$th CR user and the combining node experiences Rayleigh fading with $h_k$ being identically independent distributed (i.i.d.) complex Gaussian with zero mean and unit variance.

Since a general optimal form of the local processing function, $Q_k(\cdot)$, is intractable, we consider specifying it as a quantizer with the following form:

$$q_k = Q_k(\mathbf{r}_k) = \begin{cases} 
A_0, & l_k < T_{k,1} \\
A_1, & T_{k,1} \leq l_k < T_{k,2} \\
\vdots & \vdots \\
A_{M-1}, & l_k \geq T_{k,M-1}, \end{cases} \quad (15)$$

where

$$l_k = \frac{f(y_k | \mathcal{H}_k)}{f(y_k | \mathcal{H}_0)}, \quad (16)$$

and $q_k$ takes $M$ possible values with the quantization regions divided by $M$ thresholds, $T_{k,1}, T_{k,2}, \ldots, T_{k,M-1}$, which can be further determined to achieve the optimal performance. Because of the one-to-one correspondence between $l_k$ and $y_k$, the quantization region for $A_i$ can be transformed to $\{y_k : y_k \in R_{k,A_i}\}$.

As we have discussed, it is proper in this case to make the final decision based on the received power of $z$ in (4). To be specific, the following threshold test is applied at the combining node:

$$d = \begin{cases} 
\mathcal{H}_0, & |z|^2 < \varsigma, \\
\mathcal{H}_1, & |z|^2 \geq \varsigma, \end{cases} \quad (18)$$

where the threshold $\varsigma$ can be further determined to achieve the optimal performance.

Similarly, the probabilistic information involved can be calculated using the method introduced in the previous section.

When there are only two quantization levels, i.e., $M = 2$ in (15), the quantizer will be as simple as

$$q_k = Q_k(\mathbf{r}_k) = \begin{cases} 
0, & l_k < T, \\
1, & l_k \geq T, \end{cases} \quad (19)$$

which is equivalent to one-bit hard decision made at the $k$th CR user. Note that we let $A_0 = 0$ and $A_1 = 1$ so that the user will not send anything when $l_k$ is below the local threshold $T$ and the least amount of energy is consumed.

Define $p^{(m)}_k$ as the individual mis-detection probability that $q_k = 0$ when $B_k$ is true, which can be obtained as

$$p^{(m)}_k = \int_{R_{k,0}} f(y_k | B_k) dy_k. \quad (20)$$

Similarly, define $p^{(f)}_k$ as the individual false alarm probability that $q_k = A$ when $I_k$ is true, which can be obtained as

$$p^{(f)}_k = \int_{R_{k,A}} f(y_k | I_k) dy_k. \quad (21)$$

When each CR user is identical with the same error probabilities, denoted as $p^{(m)}$ and $p^{(f)}$, and the latencies between individual observations and final combination can be neglected as well. The conditional PDF of $|z|^2$ can be easily obtained and the miss detection (deciding $\mathcal{H}_0$ while the licensed signal is present) and false alarm (deciding $\mathcal{H}_1$ while the licensed signal is absent) probabilities are

$$P_m = 1 - \sum_{k=0}^{K} \left( \begin{array}{c} K \\ k \end{array} \right) (1 - p^{(m)})^k (p^{(m)})^{K-k} \exp \left( -\frac{\varsigma}{k A^2 + \sigma^2} \right) \quad (22)$$

and

$$P_f = \sum_{k=0}^{K} \left( \begin{array}{c} K \\ k \end{array} \right) (p^{(f)})^k (1 - p^{(f)})^{K-k} \exp \left( -\frac{\varsigma}{k A^2 + \sigma^2} \right), \quad (23)$$

respectively, where $\sigma^2$ is the variance of $w$. 

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In our simulation, with hard decisions and no reporting latencies are shown in Figure 3. Reporting channel experiences fading and the CR users are identical. Curves of the combination scheme proposed in Section 4 when the combining node while reporting.

The detection performance does not change once the received SNR operation enhances the detection performance. We also notice that as well as the curve with a single user, we can see clearly that cooperation improves the performance.

The complementary receiver operating characteristic (ROC) curves of the combination scheme proposed in Section 4 when the reporting channel experiences fading and the CR users are identical with hard decisions and no reporting latencies are shown in Figure 3. In our simulation, \( \alpha = \beta = 0.5 \text{ sec}^{-1} \), the latency between any individual observation and the final combination is uniformly distributed within \([0, 0.2]\) sec, and \( h_k = 1 \) for \( 1 \leq k \leq K \). The test threshold, \( \eta \), for making the final decision is \( \frac{1}{\alpha} \). From the detection performance curves with 4 and 6 users, as well as the curve with a single user, we can see clearly that cooperation enhances the detection performance. We also notice that the detection performance does not change once the received SNR is higher than 10 dB, which indicates that we can use the proposed combination scheme by maintaining proper received signal power at the combining node while reporting.

The complementary receiver operating characteristic (ROC) curves of the combination scheme proposed in Section 4 when the reporting channel experiences fading and the CR users are identical with hard decisions and no reporting latencies are shown in Figure 3. In our simulation, \( \alpha = \beta = 0.5 \text{ sec}^{-1} \), \( p(m) = p(f) = 0.1 \), \( \sigma^2 = 0.1 \), and \( A = 1 \). We can notice performance improvement for cooperative spectrum sensing with 4 and 6 users compared with local spectrum sensing with a single user, which proves the effectiveness of the proposed method. The curves also indicate that in this case, a few cooperative users would be enough to achieve similar detection performance as achieved by even more users.

6. CONCLUSION

We have investigated bandwidth efficient combination for cooperative spectrum sensing in CR networks. After presenting a general approach, we have discussed the optimal design of combination schemes under different cases. Our schemes allow all the sensing data to be sent simultaneously through the same channel so that the bandwidth required for reporting does not change with the number of cooperative users while maintaining reasonable performance.

7. REFERENCES