Efficient Cooperative Spectrum Sensing for Cognitive Wireless Relay Networks over Rayleigh Flat Fading Channels

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***Abstract*—This paper is concerned with cooperative spectrum sensing (CSS) mechanisms in cognitive wireless relay networks (CWRNs). Conventionally, the decision of available spectrum for cognitive radio (CR) users is carried out based on the global decision at a fusion center (FC). In this paper, we propose a new CSS scheme to improve the spectrum sensing performance by exploiting both local decisions at the CR users and global decisions at the FC. Particularly, by deriving the probabilities of missed detection and false alarm for a practical scenario where all sensing, reporting, and backward channels suffer from Rayleigh fading, we show that our proposed CSS scheme achieves an improved sensing performance over the conventional scheme. Furthermore, we propose a CSS scheme based on network coding (NC) for a specific CWRN where the transmission from a source node to a destination node is realized with the aid of two groups of CR users located in the transmission coverage of two primary users (PUs). The proposed NC-based CSS scheme helps reduce one phase of sensing for a higher system throughput compared to the conventional scheme which requires eight phases in total to monitor all available spectrums of both PUs.**

I. Introduction

Recently, cooperative communications has attracted a growing interest in wireless communications with various enhanced technologies to improve data throughput and transmission quality by exploiting spatial diversity gains [1]. With the broadcast nature of the wireless medium, data transmission from a source node to a destination node can be carried out with the aid of one or multiple intermediate nodes, i.e., relay nodes. Additionally, in order to deal with the scarcity of spectrum resources, cognitive radio (CR) was proposed as an emerging technology to improve spectrum efficiency by providing dynamic spectrum access [2]. In CR networks, spectrum holes can be opportunistically used by CR users. In order to detect the occupation and reappearance of a primary user (PU), the CR users must continuously monitor the spectrum, and thus spectrum sensing is one of the most basic elements in CR technology. Various well-known signal detection methods have been applied to spectrum sensing technology. However, the implementation of these spectrum sensing techniques is not feasible for hidden terminal problems when the CR users suffer from shadowing or severe fading effects while their nearby PUs are active.

Inspired by relaying techniques, cooperative spectrum sensing (CSS) was proposed not only to help the shadowed CR users detect the PUs but also to improve detection reliability by carrying out spectrum sensing in a cooperative manner [3]. A CSS scheme can be divided into three phases, namely sensing (SS) phase, reporting (RP) phase, and backward (BW) phase. Firstly, every CR user carries out local spectrum sensing (LSS) in the SS phase to determine locally the existence of the PU. Then, all CR users forward their local decisions to a fusion center (FC), i.e., a common receiver, in the RP phase. Lastly, the FC makes a global decision on the existence of the PU and then broadcasts this decision to all CR users in the BW phase. Over a wireless medium, the CSS scheme suffers interference and noise from all the SS, RP, and BW channels. However, most published work assumes that the RP channels are error-free [4] and that the BW channels are also error-free [3].

In this paper, we first propose a new CSS scheme to improve the spectrum sensing performance of CR networks by exploiting both the local and global decisions in spectrum sensing at each CR user. The basic idea of our proposed scheme is that each CR user combines its local decision in the SS phase with the global decision of the FC in the BW phase. Also, we take into account a practical scenario where all the SS, RP, and BW channels are characterized by Rayleigh flat fading channels. To the best of our knowledge, this has not been previously investigated. By deriving the expressions of the missed detection probability (MDP)[1] and the false alarm probability (FAP)[2], we not only show that our proposed CSS scheme achieves a better CSS performance than the conventional CSS scheme but also evaluate the effects of all the SS, RP, and BW channels.

Furthermore, we consider a cognitive wireless relay network (CWRN) where a source node $\mathcal{S}$ transmits data to a destination node $\mathcal{D}$ with the aid of N CR users. These CR users are regarded as relay nodes in wireless relay networks and are assumed to consist of two groups, which are in the transmission

[1] MDP is defined as the probability that a CR user detects an available frequency band given that a PU currently occupies that frequency.

[2] FAP is defined as the probability that a CR user senses a frequency band occupied by a PU given that the PU does not operate on that frequency band.

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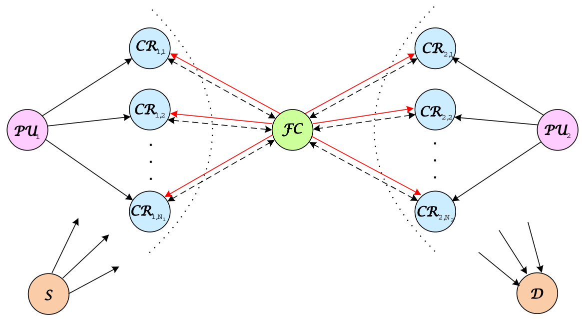

Fig. 1. System model of cognitive wireless relay network.

range of two different PUs. Inspired by cooperative spectrum sharing, the CWRN can generate a seamless transmission from $\mathcal{S}$ to $\mathcal{D}$ by exploiting some portions of the spectrum that may not be utilized by the PUs over a period of time. However, cooperative spectrum sharing in the CWRN poses the question of *how the CR users can efficiently sense the spectrum holes of both PUs*. Conventionally, the whole system requires a total of eight phases to sense the available spectrum of both PUs at each CR user, including six phases for the CSS of two groups and two phases at the FC for the exchange of spectrum information between two groups. In this paper, we further propose a new CSS scheme based on network coding (NC) for the CWRNs to reduce the number of phases by one, and thus the system throughput can be improved. NC was initially used to increase the system throughput for a lossless network [5]. The basic idea of our proposed scheme is that the FC combines two decisions of the available spectrum of two PUs and then broadcasts this combination to all the CR users in two groups. The number of signallings for the spectrum information is reduced by half with our proposed scheme when compared with the non-NC-based scheme, and thus the system throughput is considerably improved, especially when the number of frequency bands is large.

II. System Model and Local Spectrum Sensing

Figure 1 illustrates the system model of the cognitive wireless relay network under investigation. The data transmission from source node $\mathcal{S}$ to destination node $\mathcal{D}$ is accomplished with the assistance of N CR users which are referred to as relay nodes in the wireless relay network. We assume that there are in total two PUs, namely $\mathcal{PU}_1$ and $\mathcal{PU}_2$, in the network and each CR user is within the transmission range of one PU. For convenience, let N_1 and N_2 denote the number of CR users in the transmission range of $\mathcal{PU}_1$ and $\mathcal{PU}_2$, respectively, satisfying $N_1 + N_2 = N$. Accordingly, we can divide N CR users into 2 groups: $\mathcal{CR}^{(N_1)} = \{\mathcal{CR}_{1,1}, \mathcal{CR}_{1,2}, \ldots, \mathcal{CR}_{1,N_1}\}$ and $\mathcal{CR}^{(N_2)} = \{\mathcal{CR}_{2,1}, \mathcal{CR}_{2,2}, \ldots, \mathcal{CR}_{2,N_2}\}$. The two PUs are assumed to operate in a wide-band channel including K non-overlapping frequency bands $f_1, f_2, \ldots, f_K$. A spectrum indicator vector (SIV) of length K (in bits) is used to report the availability of frequency bands in the transmission range of each PU where bits '0' and '1' represent the frequency band being utilized or available, respectively. The CSS of $\mathcal{CR}^{(N_1)}$ and $\mathcal{CR}^{(N_2)}$ is carried out over a common $\mathcal{FC}$. We assume that the channels for all links are Rayleigh flat fading channels. The channel gains for the SS links $\mathcal{PU}_i \rightarrow \mathcal{CR}_{i,j}$, the RP links $\mathcal{CR}_{i,j} \rightarrow \mathcal{FC}$, and the BW links $\mathcal{FC} \rightarrow \mathcal{CR}_{i,j}$, $i = 1, 2$, $j = 1, 2, \ldots, N_i$, are denoted by $h_{P_iC_{i,j}}$, $h_{C_{i,j}F}$, and $h_{FC_{i,j}}$, respectively. All the channels are assumed to be time-invariant over the whole transmission of both the data and the SIV, and assumed to be known to all the nodes in the network.

Over the SS channel, the received signal at $\mathcal{CR}_{i,j}$, $i = 1, 2$, $j = 1, 2, \ldots, N_i$, can be expressed as

$$\mathbf{r}_{i,j}^{(SS)} = \begin{cases} h_{P_iC_{i,j}}\mathbf{x}_i + \mathbf{n}_{i,j}^{(SS)}, & \mathcal{H}_1^{(\mathcal{PU}_i)}, \\ \mathbf{n}_{i,j}^{(SS)}, & \mathcal{H}_0^{(\mathcal{PU}_i)}. \end{cases} \tag{1}$$

where $\mathbf{x}_i$ is the transmitted signal from $\mathcal{PU}_i$ and $\mathbf{n}_{i,j}^{(SS)}$ is the independent circularly symmetric complex Gaussian (CSCG) noise vector at $\mathcal{CR}_{i,j}$ over the SS channel. Here, $\mathcal{H}_1^{(\mathcal{PU}_i)} = \{\mathcal{H}_{1,1}^{(\mathcal{PU}_i)}, \mathcal{H}_{1,2}^{(\mathcal{PU}_i)}, \ldots, \mathcal{H}_{1,K}^{(\mathcal{PU}_i)}\}$ and $\mathcal{H}_0^{(\mathcal{PU}_i)} = \{\mathcal{H}_{0,1}^{(\mathcal{PU}_i)}, \mathcal{H}_{0,2}^{(\mathcal{PU}_i)}, \ldots, \mathcal{H}_{0,K}^{(\mathcal{PU}_i)}\}$ denote the hypothesis that the frequency bands are occupied by $\mathcal{PU}_i$ and the hypothesis that the frequency bands are available for CR users, respectively. We notice that the vectors in (1) have length K which corresponds to the number of frequency bands.

Then, following an energy detection rule for unknown signals over fading channels [6], $\mathcal{CR}_{i,j}$ can detect the usage of a k-th frequency band, $k = 1, 2, \ldots, K$, at $\mathcal{PU}_i$ by comparing the energy of the received signal $\mathbf{r}_{i,j}^{(SS)}[k]$ at the k-th frequency band with a corresponding energy threshold $\mathcal{E}_{i,j}[k]$, i.e.,

$$E\left[\mathbf{r}_{i,j}^{(SS)}[k]\right] \gtrless_{\mathcal{H}_{0,k}^{(\mathcal{CR}_{i,j})}}^{\mathcal{H}_{1,k}^{(\mathcal{CR}_{i,j})}} \mathcal{E}_{i,j}[k], \tag{2}$$

where $E[.]$ is the energy measurement of a signal. Here, $\mathcal{H}_{1,k}^{(\mathcal{CR}_{i,j})}$ and $\mathcal{H}_{0,k}^{(\mathcal{CR}_{i,j})}$ denote the estimated hypotheses at $\mathcal{CR}_{i,j}$ that the k-th frequency band is occupied or unoccupied, respectively, by $\mathcal{PU}_i$. Let $\mathbf{s}_{i,j}^{(SS)}$ denote the local SIV estimated at $\mathcal{CR}_{i,j}$ over the SS channel $h_{P_iC_{i,j}}$. We can formulate the k-th element, $k = 1, 2, \ldots, K$, of $\mathbf{s}_{i,j}^{(SS)}$ as

$$\mathbf{s}_{i,j}^{(SS)}[k] = \begin{cases} 0, \text{ if } E\left[\mathbf{r}_{i,j}^{(SS)}[k]\right] \geqslant \mathcal{E}_{i,j}[k], \text{ i.e., } \mathcal{H}_{1,k}^{(\mathcal{CR}_{i,j})}, \\ 1, \text{ otherwise, i.e., } \mathcal{H}_{0,k}^{(\mathcal{CR}_{i,j})}. \end{cases} \tag{3}$$

III. Proposed Cooperative Spectrum Sensing

A. Proposed CSS Scheme for A Group of CR Users

For simplicity, we investigate the CSS scheme performed at only one group of CR users, e.g., $\mathcal{CR}^{(N_1)}$. The CSS scheme for the remaining group of CR users, $\mathcal{CR}^{(N_2)}$, can be similarly obtained. The proposed CSS scheme consists of three phases:

1) Sensing Phase: In SS phase, each CR user $\mathcal{CR}_{1,j}$, $j = 1, 2, \ldots, N_1$, locally senses the available frequency bands of $\mathcal{PU}_1$ over the SS channel $h_{P_1C_{1,j}}$, and then makes a binary decision in terms of an SIV denoted by $\mathbf{s}_{1,j}^{(SS)}$ (see (3)).

2) Reporting Phase: Over the RP channels, $\mathcal{CR}_{1,j}$, $j = 1, 2, \ldots, N_1$, forwards $\mathbf{s}_{1,j}^{(SS)}$ to $\mathcal{FC}$. The received signals at $\mathcal{FC}$ from $\mathcal{CR}_{1,j}$ can be written by

$$\mathbf{r}_{1,j}^{(RP)} = \sqrt{\Lambda_{1,j}} h_{C_{1,j}F} \mathbf{x}_{1,j}^{(SS)} + \mathbf{n}_{1,j}^{(RP)}, \tag{4}$$

where $\Lambda_{1,j}$ is the transmission power of $\mathcal{CR}_{1,j}$, $\mathbf{x}_{1,j}^{(SS)}$ is the binary phase shift keying modulated version of $\mathbf{s}_{1,j}^{(SS)}$, and $\mathbf{n}_{1,j}^{(RP)}$ is the independent CSCG noise vector at $\mathcal{FC}$ over the RP channel with each entry having zero mean and variance of N_0.

Then, $\mathcal{FC}$ processes to decode the received signals from each $\mathcal{CR}_{1,j}$, $j = 1, 2, \ldots, N_1$ as $\mathbf{s}_{1,j}^{(RP)}$. Combining all the decoded SIVs $\{\mathbf{s}_{1,j}^{(RP)}\}$ from all $\{\mathcal{CR}_{1,j}\}$, $\mathcal{FC}$ makes a global decision using OR rule[3] as follows:

$$\mathbf{s}_{FC_1}[k] = \begin{cases} 0, & \text{if } \sum_{j=1}^{N_1} \mathbf{s}_{1,j}^{(RP)}[k] < N_1, \text{ i.e., } \mathcal{H}_{1,k}^{(\mathcal{FC}_1)}, \\ 1, & \text{otherwise, i.e., } \mathcal{H}_{0,k}^{(\mathcal{FC}_1)}, \end{cases} \tag{5}$$

where $\mathbf{s}_{FC_1}$ of length K denotes the global SIV estimated at $\mathcal{FC}$ for the first group of CR users and $k = 1, 2, \ldots, K$. Here, $\mathcal{H}_{1,k}^{(\mathcal{FC}_1)}$ and $\mathcal{H}_{0,k}^{(\mathcal{FC}_1)}$ denote the estimated hypotheses at $\mathcal{FC}$ of the k-th frequency band occupied or unoccupied, respectively, by $\mathcal{PU}_1$.

3) Backward Phase: In the BW phase, the FC broadcasts the global SIV to all CR users over BW channels. The received signal at $\mathcal{CR}_{1,j}$, $j = 1, 2, \ldots, N_1$, can be written by

$$\mathbf{r}_{1,j}^{(BW)} = \sqrt{\Lambda_{FC}} h_{FC_{1,j}} \mathbf{x}_{FC_1} + \mathbf{n}_{1,j}^{(BW)}, \tag{6}$$

where Λ_{FC} is the transmission power of $\mathcal{FC}$, $\mathbf{x}_{FC_1}$ is the modulated version of $\mathbf{s}_{FC_1}$, and $\mathbf{n}_{1,j}^{(BW)}$ is the independent CSCG noise vector at $\mathcal{CR}_{1,j}$ over the BW channel with each entry having zero mean and variance of N_0. Then, $\mathcal{CR}_{1,j}$ decodes the received signal from $\mathcal{FC}$ as $\mathbf{s}_{1,j}^{(BW)}$. In our proposed CSS scheme, each CR user combines its local SIV $\mathbf{s}_{1,j}^{(SS)}$ with the global SIV $\mathbf{s}_{1,j}^{(BW)}$ using the OR rule as follows:

$$\mathbf{s}_{CR_{1,j}}[k] = \begin{cases} 0, \text{if } (\mathbf{s}_{1,j}^{(SS)}[k] + \mathbf{s}_{1,j}^{(BW)}[k]) < 2, \text{ i.e., } \bar{\mathcal{H}}_{1,k}^{(\mathcal{CR}_{1,j})}, \\ 1, \text{otherwise, i.e., } \bar{\mathcal{H}}_{0,k}^{(\mathcal{CR}_{1,j})}. \end{cases} \tag{7}$$

where $\mathbf{s}_{CR_{1,j}}$ denotes the final SIV at $\mathcal{CR}_{1,j}$, $k = 1, 2, \ldots, K$, and, $\bar{\mathcal{H}}_{1,k}^{(\mathcal{CR}_{1,j})}$ and $\bar{\mathcal{H}}_{0,k}^{(\mathcal{CR}_{1,j})}$ denote the globally estimated hypotheses at $\mathcal{CR}_{1,j}$, $j = 1, 2, \ldots, N_1$, of the k-th frequency band occupied and unoccupied, respectively, by $\mathcal{PU}_1$ considering both the local and global SIVs.

Remark 1 (*Higher Reliability in Spectrum Sensing*)**.** The proposed CSS scheme can determine the availability of frequency bands more reliably than the conventional scheme. In the conventional scheme, the global SIV received at $\mathcal{CR}_{1,j}$ from the FC is also the final SIV, which means that the decision at $\mathcal{CR}_{1,j}$ depends totally on the decision at the FC. Instead, in our proposed scheme, the final SIV at $\mathcal{CR}_{1,j}$ is the combination of two SIVs obtained from both the LSS and CSS. As shown in (7), the hypothesis $\bar{\mathcal{H}}_{0,k}^{(\mathcal{CR}_{1,j})}$ is decided by $\mathbf{s}_{CR_{1,j}}[k] = 1$ if $\mathbf{s}_{1,j}^{(SS)}[k] = 1$ and $\mathbf{s}_{1,j}^{(BW)}[k] = 1$, which correspond to the hypotheses $\mathcal{H}_{0,k}^{(\mathcal{CR}_{1,j})}$ and $\mathcal{H}_{0,k}^{(\mathcal{FC}_1)}$. It can be seen that the frequency bands are finally determined to be available at $\mathcal{CR}_{1,j}$ only if both the LSS and CSS indicate that $\mathcal{PU}_1$ does not occupy these frequency bands. Therefore, the probability of missed detection is reduced.

[3] The OR rule was shown in [7] to give the best CSS performance compared to the AND and majority rules.

B. Proposed NC-based CSS scheme for Two Groups of CR Users in CWRN

In this subsection, let us investigate a CWRN consisting of $\mathcal{S}$, $\mathcal{D}$, $\mathcal{CR}^{(N_1)}$, and $\mathcal{CR}^{(N_2)}$ (see Fig. 1). In order to realize a continuous transmission from $\mathcal{S}$ to $\mathcal{D}$ with the assistance of $\mathcal{CR}^{(N_1)}$ and $\mathcal{CR}^{(N_2)}$, the spectrum can be shared in a cooperative manner to efficiently exploit the frequency bands that are not occupied by $\mathcal{PU}_1$ and $\mathcal{PU}_2$. Thus, all the CR users in $\mathcal{CR}^{(N_1)}$ and $\mathcal{CR}^{(N_2)}$ are required to sense the spectrum holes of both $\mathcal{PU}_1$ and $\mathcal{PU}_2$.

The CSS scheme for each group of CR users, as previously presented, consists of three phases to detect the available spectrum in the coverage of the corresponding PU. In order to help two groups know the spectrum information of each other, the conventional scheme requires two additional phases at $\mathcal{FC}$ to forward the global SIV of a group of CR users to another group, i.e., $\mathcal{FC}$ sequentially forwards $\mathbf{s}_{FC_1}$ and $\mathbf{s}_{FC_2}$ to $\mathcal{CR}^{(N_2)}$ and $\mathcal{CR}^{(N_1)}$, respectively. Accordingly, this results in a total of eight phases in the conventional CSS scheme. Using the concept of NC, we propose a NC-based CSS scheme to reduce the exchanging time of the SIVs between $\mathcal{CR}^{(N_1)}$ and $\mathcal{CR}^{(N_2)}$. The proposed NC-based CSS scheme consists of seven phases as follows: SS, RP, and BW phases for $\mathcal{CR}^{(N_1)}$; SS, RP, and BW phases for $\mathcal{CR}^{(N_2)}$; and an exchange (EX) phase between $\mathcal{CR}^{(N_1)}$ and $\mathcal{CR}^{(N_2)}$.

Following the proposed CSS scheme for each group of CR users, the final SIV at $\mathcal{CR}_{i,j}$, $i = 1, 2$, $j = 1, 2, \ldots, N_i$, and the global SIV at $\mathcal{FC}$ for the i-th group are given by $\mathbf{s}_{CR_{i,j}}$ and $\mathbf{s}_{FC_i}$, respectively. In the EX phase of the proposed NC-based CSS scheme, $\mathcal{FC}$ combines the global SIVs determined after two RP phases, i.e., $\mathbf{s}_{FC_1}$ and $\mathbf{s}_{FC_2}$, as

$$\mathbf{s}_{FC} = \mathbf{s}_{FC_1} \oplus \mathbf{s}_{FC_2}, \tag{8}$$

where $\oplus$ denotes the XOR operator and $\mathbf{s}_{FC}$ is the NC-based combined SIV at $\mathcal{FC}$. Then, $\mathcal{FC}$ forwards $\mathbf{s}_{FC}$ to all CR users in two groups. The received signal at each CR user $\mathcal{CR}_{i,j}$, $i = 1, 2$, $j = 1, 2, \ldots, N_i$, can be written as

$$\mathbf{r}_{i,j}^{(EX)} = \sqrt{\Lambda_{FC}} h_{FC_{i,j}} \mathbf{x}_{FC} + \mathbf{n}_{i,j}^{(EX)}, \tag{9}$$

where $\mathbf{x}_{FC}$ is the modulated version of $\mathbf{s}_{FC}$, and $\mathbf{n}_{i,j}^{(EX)}$ is the independent CSCG noise vector at $\mathcal{CR}_{i,j}$ in the EX phase with each entry having zero mean and variance of N_0. Then, $\mathcal{CR}_{i,j}$ decodes the received signal as $\mathbf{s}_{i,j}^{(EX)}$. Note that the decoded signal at $\mathcal{CR}_{i,j}$ of the transmitted signal $\mathbf{s}_{FC_i}$ in the BW phase is given by $\mathbf{s}_{i,j}^{(BW)}$ (see (6)). Thus, $\mathcal{CR}_{i,j}$ in the i-th group can detect the spectrum information of the $\bar{i}$-th group, $\bar{i} = 1, 2$, $\bar{i} \neq i$, as $\mathbf{s}^{(\bar{i})}_{CR_{i,j}}$ based on the concept of NC, i.e.,

$$\mathbf{s}^{(\bar{i})}_{CR_{i,j}} = \mathbf{s}^{(EX)}_{i,j} \oplus \mathbf{s}^{(BW)}_{i,j}. \tag{10}$$

Remark 2 (*Higher System Throughput with NC*)**.** The proposed NC-based CSS scheme for two groups of CR users in the CWRN achieves a higher system throughput than the conventional CSS scheme. Let $T^{(SS)}_{i,j}$ and $T^{(RP)}_{i,j}$ denote the local sensing time and reporting time, respectively, for a frequency band at the j-th CR user in the i-group, $i = 1, 2$, $j = 1, 2, \ldots, N_i$. Also, let $T^{(BW)}$ and $T^{(EX)}$ denote the backward time and the exchange time, respectively, at FC for a frequency band. It can be seen that the conventional CSS scheme requires a total time of $[K(\sum_{i=1}^{2}\sum_{j=1}^{N_i} T^{(SS)}_{i,j} + T^{(RP)}_{i,j}) + 2KT^{(BW)} + 2KT^{(EX)}]$ whilst the total time in our proposed CSS scheme is $[K(\sum_{i=1}^{2}\sum_{j=1}^{N_i} T^{(SS)}_{i,j} + T^{(RP)}_{i,j}) + 2KT^{(BW)} + KT^{(EX)}]$. Thus, the proposed NC-based CSS scheme reduces the time of spectrum sensing in the whole system by $KT^{(EX)}$, which accordingly results in a higher system throughput.

IV. Performance Analysis of Cooperative Spectrum Sensing

In this section, we derive the expressions of two performance metrics of the spectrum sensing in CWRNs including the missed detection probability (MDP) and the false alarm probability (FAP) over a practical scenario where all the SS, RP, and BW channels are characterized by Rayleigh flat fading channels. For convenience, let $P^{(A)}_m$ and $P^{(A)}_f$, $A \in \{\mathcal{CR}_{i,j}, \mathcal{FC}\}$, $i = 1, 2$, $j = 1, 2, \ldots, N_i$, denote the MDP and FAP, respectively, at node A.

For the LSS at an CR user $\mathcal{CR}_{i,j}$, $i = 1, 2$, $j = 1, 2, \ldots, N_i$, the average FAP and MDP of the k-th frequency band over the SS channels are given by

$$P^{(\mathcal{CR}_{i,j})}_f = \frac{\Gamma\left(\mu, \frac{\mathcal{E}_{i,j}[k]}{2}\right)}{\Gamma(\mu)}, \tag{11}$$

and (12) [6] (see below), where μ is the time-bandwidth product, $\gamma^{(\mathcal{CR}_{i,j})}_{P_iC_{i,j}}$ is average signal-to-noise ratio (SNR) at $\mathcal{CR}_{i,j}$ over the SS channel $h_{P_iC_{i,j}}$, and $\Gamma[a,b]$ is the upper incomplete gamma function defined as $\Gamma[a,b] \triangleq \int_b^\infty t^{a-1}e^{-t}dt$.

Now, let us analyse the CSS scheme performed at only one group of CR users, e.g., $\mathcal{CR}^{(N_1)}$. The analysis of the CSS scheme for the remaining group of CR users, $\mathcal{CR}^{(N_2)}$, can be similarly obtained. From (5), the FAP and MDP at the FC can be written as

$$\begin{aligned} P^{(\mathcal{FC}_1)}_f &= \Pr\{\mathcal{H}^{(\mathcal{FC}_1)}_{1,k} | \mathcal{H}^{(\mathcal{PU}_1)}_{0,k}\} = \Pr\{\mathbf{s}_{FC_1}[k] = 0 | \mathbf{x}_1 = 0\} \\ &= 1 - \prod_{j=1}^{N_1} \Pr\{\mathbf{s}^{(RP)}_{1,j}[k] = 1 | \mathbf{x}_1 = 0\}, \end{aligned} \tag{13}$$

$$\begin{aligned} P^{(\mathcal{FC}_1)}_m &= \Pr\{\mathcal{H}^{(\mathcal{FC}_1)}_{0,k} | \mathcal{H}^{(\mathcal{PU}_1)}_{1,k}\} = \Pr\{\mathbf{s}_{FC_1}[k] = 1 | \mathbf{x}_1 \neq 0\} \\ &= \prod_{j=1}^{N_1} \Pr\{\mathbf{s}^{(RP)}_{1,j}[k] = 1 | \mathbf{x}_1 \neq 0\}. \end{aligned} \tag{14}$$

Over a Rayleigh flat fading channel h_{AB}, the bit error probability (BEP) for signal transmission is given by $P_b(E_{AB}) = \phi(\gamma)$ [8], where γ is the average SNR and $\phi(x) \triangleq \frac{1}{2}\left(1 - \sqrt{\frac{x}{1+x}}\right)$. Thus, taking into account the noisy RP channels $\{h_{C_{1,j}F}\}$, $j = 1, 2, \ldots, N_1$, the FAP and MDP at the FC are given by

$$\begin{aligned} P^{(\mathcal{FC}_1)}_f = 1 - \prod_{j=1}^{N_1} &[(1 - P^{(\mathcal{CR}_{1,j})}_f)(1 - P_b(E_{C_{1,j}F})) \\ &+ P^{(\mathcal{CR}_{1,j})}_f P_b(E_{C_{1,j}F})], \end{aligned} \tag{15}$$

$$\begin{aligned} P^{(\mathcal{FC}_1)}_m = \prod_{j=1}^{N_1} &[P^{(\mathcal{CR}_{1,j})}_m (1 - P_b(E_{C_{1,j}F})) \\ &+ (1 - P^{(\mathcal{CR}_{1,j})}_m) P_b(E_{C_{1,j}F})]. \end{aligned} \tag{16}$$

Here, $P_b(E_{C_{1,j}F}) = \phi(\gamma^{(\mathcal{FC})}_{C_{1,j}F})$, where $\gamma^{(\mathcal{FC})}_{C_{1,j}F}$ denotes the SNR at $\mathcal{FC}$ over the RP channel $h_{C_{1,j}F}$.

Then, in order to help each CR user decide the availability of spectrum, the FC needs to forward its decision to all the CR users over the BW channels. Let $P'^{(\mathcal{CR}_{1,j})}_f$ and $P'^{(\mathcal{CR}_{1,j})}_m$ denote the FAP and MDP of the final decision at $\mathcal{CR}_{1,j}$ over the BW channels in our proposed CSS scheme. From (7), $P'^{(\mathcal{CR}_{1,j})}_f$ and $P'^{(\mathcal{CR}_{1,j})}_m$ can be derived as

$$\begin{aligned} P'^{(\mathcal{CR}_{1,j})}_f &= \Pr\{\bar{\mathcal{H}}^{(\mathcal{CR}_{1,j})}_{1,k} | \mathcal{H}^{(\mathcal{PU}_1)}_{0,k}\} = \Pr\{\mathbf{s}_{CR_{1,j}}[k] = 0 | \mathbf{x}_1 = 0\} \\ &= 1 - \Pr\{\mathbf{s}^{(SS)}_{1,j}[k] = 1 | \mathbf{x}_1 = 0\} \Pr\{\mathbf{s}^{(BW)}_{1,j}[k] = 1 | \mathbf{x}_1 = 0\}, \end{aligned} \tag{17}$$

$$\begin{aligned} P'^{(\mathcal{CR}_{1,j})}_m &= \Pr\{\bar{\mathcal{H}}^{(\mathcal{CR}_{1,j})}_{0,k} | \mathcal{H}^{(\mathcal{PU}_1)}_{1,k}\} = \Pr\{\mathbf{s}_{CR_{1,j}}[k] = 1 | \mathbf{x}_1 \neq 0\} \\ &= \Pr\{\mathbf{s}^{(SS)}_{1,j}[k] = 1 | \mathbf{x}_1 \neq 0\} \Pr\{\mathbf{s}^{(BW)}_{1,j}[k] = 1 | \mathbf{x}_1 \neq 0\}. \end{aligned} \tag{18}$$

In practice, the BW channels also suffer from fading and noise. Thus, the FAP and MDP at $\mathcal{CR}_{1,j}$, $j = 1, 2, \ldots, N_1$, over the noisy BW channels $h_{FC_{1,j}}$ can be written as

$$\begin{aligned} P'^{(\mathcal{CR}_{1,j})}_f = 1 - &[(1 - P^{(\mathcal{CR}_{1,j})}_f)(1 - P_b(E_{FC_{1,j}})) + P^{(\mathcal{CR}_{1,j})}_f P_b(E_{FC_{1,j}})] \\ &\times [(1 - P^{(\mathcal{FC}_1)}_f)(1 - P_b(E_{FC_{1,j}})) + P^{(\mathcal{FC}_1)}_f P_b(E_{FC_{1,j}})], \end{aligned} \tag{19}$$

$$\begin{aligned} P'^{(\mathcal{CR}_{1,j})}_m = &[P^{(\mathcal{CR}_{1,j})}_m (1 - P_b(E_{FC_{1,j}})) + (1 - P^{(\mathcal{CR}_{1,j})}_m) P_b(E_{FC_{1,j}})] \\ &\times [P^{(\mathcal{FC}_1)}_m (1 - P_b(E_{FC_{1,j}})) + (1 - P^{(\mathcal{FC}_1)}_m) P_b(E_{FC_{1,j}})], \end{aligned} \tag{20}$$

where $P_b(E_{FC_{1,j}}) = \phi(\gamma^{(\mathcal{CR}_{1,j})}_{FC_{1,j}})$ and $\gamma^{(\mathcal{CR}_{1,j})}_{FC_{1,j}}$ denotes the SNR at $\mathcal{CR}_{1,j}$ over the BW channel $h_{FC_{1,j}}$.

Remark 3 (*Better Sensing Performance with Our Proposed CSS Scheme*)**.** The proposed CSS scheme at the CR users achieves a better performance than the conventional scheme in terms of MDP. In fact, following the conventional scheme, the final SIV at the CR users is obtained from the global SIV at the FC, which means that $\mathbf{s}_{CR_{1,j}}$, $j = 1, 2, \ldots, N_1$, depends totally on $\mathbf{s}_{FC_1}$. Thus, the MDP of the conventional CSS scheme at $\mathcal{CR}_{1,j}$ is given by

$$P''^{(\mathcal{CR}_{1,j})}_m = P^{(\mathcal{FC}_1)}_m (1 - P_b(E_{FC_{1,j}})) + (1 - P^{(\mathcal{FC}_1)}_m) P_b(E_{FC_{1,j}}), \tag{21}$$

$$P_m^{(\mathcal{CR}_{i,j})} = 1 - e^{-\frac{\mathcal{E}_{i,j}[k]}{2}} \sum_{l=0}^{\mu-2} \frac{\mathcal{E}_{i,j}^l[k]}{l!2^l} - \left(\frac{1+\gamma_{P_iC_{i,j}}^{(\mathcal{CR}_{i,j})}}{\gamma_{P_iC_{i,j}}^{(\mathcal{CR}_{i,j})}} \right)^{\mu-1} \left[e^{-\frac{\mathcal{E}_{i,j}[k]}{2\left(1+\gamma_{P_iC_{i,j}}^{(\mathcal{CR}_{i,j})}\right)}} - e^{-\frac{\mathcal{E}_{i,j}[k]}{2}} \sum_{l=0}^{\mu-2} \frac{\mathcal{E}_{i,j}^l[k](\gamma_{P_iC_{i,j}}^{(\mathcal{CR}_{i,j})})^l}{l!2^l \left(1+\gamma_{P_iC_{i,j}}^{(\mathcal{CR}_{i,j})}\right)^l} \right], \quad (12)$$

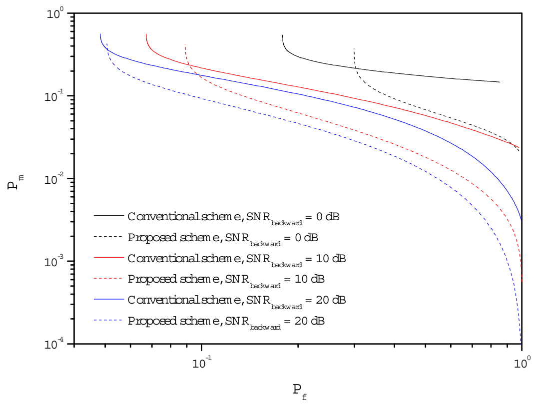

Fig. 2. Comparison of two CSS schemes over BW links with 2 CR users.

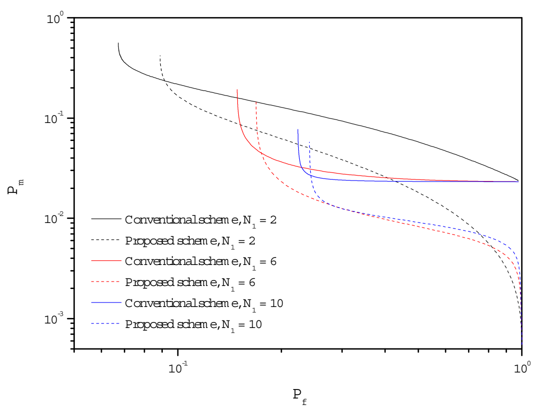

Fig. 3. Comparison of two CSS schemes over BW links with various N_1.

where $P_m^{(\mathcal{FC}_1)}$ is given by (16). From (20) and (21), it can be seen that $P_m^{''(\mathcal{CR}_{1,j})} > P_m^{'(\mathcal{CR}_{1,j})}$, i.e., our proposed CSS scheme achieves a lower MDP than the conventional scheme.

V. Numerical Results

In this section, we present numerical results of the MDP and FAP using various spectrum sensing schemes. Specifically, the relationship between the MDP and the FAP is represented by the complementary receiver operating characteristic (CROC), which is defined as the MDP versus the FAP.

Fig. 2 shows the CROC of both our proposed CSS scheme and the conventional scheme with respect to various SNR values of the BW channel. The CROC curves are plotted for the CSS at $\mathcal{CR}_{1,1}$ in the first group of CR users including 2 CR users $\mathcal{CR}_{1,1}$ and $\mathcal{CR}_{1,2}$. We assume that the time-bandwidth product $\mu = 5$ and the SNRs of the SS, RP, and BW channels are: $\gamma_{C_{1,1}F}^{(\mathcal{FC})} = \gamma_{C_{1,2}F}^{(\mathcal{FC})} = \gamma_{P_1C_{1,1}}^{(\mathcal{CR}_{1,1})} = \gamma_{P_1C_{1,2}}^{(\mathcal{CR}_{1,2})} = 10$ dB and $\gamma_{FC_{1,1}}^{(\mathcal{CR}_{1,1})} \in \{0, 10, 20\}$ dB. It can be seen that our proposed CSS scheme achieves better sensing performance than the conventional scheme for all SNR values of the BW channels. This observation confirms the statements in Remarks 1 and 3 about the improved reliability of spectrum sensing with our proposed CSS scheme. In fact, in our proposed scheme, the combination of the LSS and CSS at the CR user results in better sensing performance at the CR users.

Investigating the effects of the number of CR users on the sensing performance, Fig. 3 plots the CROC of both our proposed CSS scheme and the conventional scheme with respect to various numbers of CR users (i.e., N_1). We assume that the SNRs of the SS, RP, and BW channels are 10 dB and N_1 varies in $\{2, 6, 10\}$. It can be observed that our proposed scheme achieves improved performance over the conventional scheme for all values of N_1. This also confirms the statements in Remarks 1 and 3 regarding the improved sensing performance with our proposed CSS scheme.

VI. Conclusions

In this paper, we have proposed a CSS scheme for CWRNs to improve the sensing performance by exploiting both the local decisions and global decisions. An analysis of the MDP and FAP has been carried out with respect to the SNRs of SS, RP, and BW channels, which reflects well the impact of quality of all the links upon the sensing performance. Moreover, for the exchange of spectrum information between two groups of CR users, we have proposed an NC-based CSS scheme to reduce the number of signallings for a higher system throughput. For future work, one can investigate the effects of noise on the accuracy of the recovered signals in the NC-based CSS scheme.

References

[1] A. Sendonaris, E. Erkip, and B. Aazhang, “User cooperation diversity - Part I. System description,” *IEEE Trans. Commun.*, vol. 51, no. 11, pp. 1927–1938, Nov. 2003.

[2] I. Mitola, J. and J. Maguire, G.Q., “Cognitive radio: Making software radios more personal,” *IEEE Pers. Commun.*, vol. 6, no. 4, pp. 13–18, Aug. 1999.

[3] W. Zhang and K. Letaief, “Cooperative spectrum sensing with transmit and relay diversity in cognitive radio networks,” *IEEE Trans. Wireless Commun.*, vol. 7, no. 12, pp. 4761–4766, Dec. 2008.

[4] G. Ganesan and Y. Li, “Cooperative spectrum sensing in cognitive radio, part I: Two user networks,” *IEEE Trans. Wireless Commun.*, vol. 6, no. 6, pp. 2204–2213, Jun. 2007.

[5] R. Ahlswede, N. Cai, S.-Y. Li, and R. Yeung, “Network information flow,” *IEEE Trans. Inf. Theory*, vol. 46, no. 4, pp. 1204–1216, Jul. 2000.

[6] F. F. Digham, M.-S. Alouini, and M. K. Simon, “On the energy detection of unknown signals over fading channels,” *IEEE Trans. Commun.*, vol. 55, no. 1, pp. 21–24, Jan. 2007.

[7] A. Ghasemi and E. S. Sousa, “Opportunistic spectrum access in fading channels through collaborative sensing,” *J. Commun.*, vol. 2, no. 2, pp. 71–82, Mar. 2007.

[8] M. K. Simon and M.-S. Alouini, *Digital Communication over Fading Channels*, 2nd ed. John Wiley & Sons, 2005.