Cooperative Spectrum Sensing in Cognitive Radio Network Using Selective Soft-Information Fusion Scheme

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***Abstract*—This paper examines the effectiveness of a cognitive radio (CR) network using a conventional energy detector and the selective soft-information fusion rule when confronted with faulty control channels. Using a selective soft-information fusion scheme, we have formulated a mathematical expression that provides a closed-form solution for both the probability of a false alarm and the probability of a missed detection. Several new and extant results are presented as special scenarios in the proposed solution. We also investigate optimal values of the selective soft fusion's threshold and spectrum-aware CR users by minimizing the CR network's average error rate. Subsequently, numerical results illustrate the proposed CR network's theoretical findings.**

***Index Terms*—Cognitive radio, conventional energy detection, selective soft-information fusion rule, cognitive radio network, average error rate.**

I. Introduction

The cognitive radio (CR) technology enables the dynamic allocation of authorized users' (AUs) spectrum to spectrum-aware CR (SCR) users without causing interference to the AU [1], [2]. To achieve this, SCR users must consistently monitor the spectrum allocated to AU to determine its current status [3]. Numerous spectrum sensing techniques have been extensively investigated in the available literature to detect the presence of AU within the spectrum [4]–[9]. All of the previously mentioned works focused on utilizing a single SCR user for spectrum sensing purposes. Since there are fading and shadowing effects in the wireless communication channel, a single CR user's sensing performance is unreliable. To enhance the performance of spectrum sensing, the concept of cooperative spectrum sensing (CSS) has been introduced [10]–[14]. In the context of CSS, all the SCR users in the CR network report their sensed observations to the merging point. The merging point then fuses all the reported observations to determine AU's current status. Furthermore, several optimal fusion schemes have been proposed to accomplish different objectives. For example, some literatures have investigated an optimal soft-information fusion rule and an optimal N-out-of-K fusion rule in order to minimize the total error rate at the merging point [15]–[17]. All of the aforementioned studies focused on proposing optimal fusion rules, assuming the presence of an error-free control channel. In practical scenarios, the control channels are faulty due to the errors caused by fading and shadowing effects. A few studies have addressed the issue of imperfect control channels, considering that the channels between the SCR users and the merging point are subject to errors [18], [19]. Furthermore, despite the overhead it incurs, all the existing literature employs maximal-ratio combining (MRC) at the merging point [20]. To mitigate the overhead at the merging point, we have proposed a selective soft-information (SSI) fusion scheme at the merging point. In the context of the SSI fusion scheme, the CR user with the maximum decision statistic is chosen at the merging point to make the final decision. Therefore, in this paper, we emphasize the importance of investigating the performance of a CR network utilizing a SSI fusion scheme and conventional energy detector (CED), specifically in the presence of faulty control channels. This paper presents several significant contributions, summarized as follows:

- The proposed CR network's false-alarm and missed-detection probabilities are derived in the presence of faulty control channels using the CED and SSI fusion scheme.
- We analyze and discuss special scenarios for the proposed CR network.

II. System Model

We examine a CR network, depicted in Fig. 1, consisting of L SCR users with a CED and a merging point. A merging point utilizes a SSI fusion scheme to distinguish between two hypotheses: $\mathcal{H}_0$ indicating AU absence in the spectrum, and $\mathcal{H}_1$ indicating AU existence in the spectrum. In the CR network, all the SCR users independently observe the AU through Rayleigh faded sensing channels. Therefore, the received signal of the l^{th} SCR user denoted as $z_l(t)$ for the time slot n is given independently under $\mathcal{H}_0$ and $\mathcal{H}_1$ as follows:

$$z_l(n) = \begin{cases} w_l(n) \sim \mathcal{CN}(0, \sigma^2_{w_l}) & \mathcal{H}_0, \\ h_l^{(s)} y(n) + w_l(n) \sim \mathcal{CN}(0, E_y \sigma^2_{h_l^{(s)}} + \sigma^2_{w_l}) & \mathcal{H}_1, \end{cases} \tag{1}$$

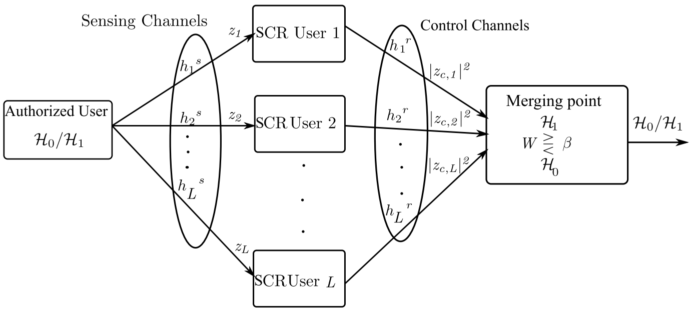

Fig. 1. Schematic representation of spectrum sensing in the CR network using the selective soft-information fusion scheme.

Here, the notation $\mathcal{CN}(0, \sigma^2)$ represents a zero-mean complex Gaussian random variable with a variance of σ^2. $w_l(n) \sim \mathcal{CN}(0, \sigma^2_{w_l})$ denotes the noise in the sensing channel at the l^{th} SCR user. $h_l^{(s)}$ is the channel coefficient from the AU to the l^{th} SCR user, following a Rayleigh distribution, with a variance of $\sigma^2_{h_l(s)}$. The signal $y(n)$ corresponds to the unknown transmitted signal from the AU during time slot n, possessing an energy of E_y. The SNR at the sensing channel of the l^{th} SCR user is denoted by ζ_{s_l} and is calculated as $\zeta_{s_l} = \frac{E_y \sigma^2_{h_l(s)}}{\sigma^2_{w_l}}$. Under the assumption of no transmission delay, each SCR user promptly transmits its observation to the merging point through independent Rayleigh faded reporting channels. The received signal at the merging point during time slot n can be expressed as follows:

$$z_{c,l}(n) = \begin{cases} h_l^{(r)} w_l(n) + w_{c_l}(n) & \\ \quad \sim \mathcal{CN}(0,1) & \mathcal{H}_0, \\ h_l^{(r)}(h_l^{(s)} y(n) + w_l(n)) + w_{c_l}(n) & \\ \quad \sim \mathcal{CN}(0, \zeta+1) & \mathcal{H}_1, \end{cases} \quad (2)$$

Here, $w_{c_l}(n) \sim \mathcal{CN}(0, \sigma^2_{w_{c,l}})$ represents the noise between the l^{th} SCR user and the merging point. $h_l^{(r)}$ is the channel coefficient from the l^{th} SCR user to the merging point, which follows a Rayleigh distribution with a variance of $\sigma^2_{h_l(r)}$. The end-to-end SNR between the AU and the merging point through a SCR user is denoted as ζ_l and can be calculated using $\zeta_l = \frac{\zeta_{r_l} \zeta_{s_l} \sigma^2_{w_l}}{\zeta_{r_l} \sigma^2_{w_l} + \zeta_{s_l}}$. Here, ζ_{r_l} represents the control channel SNR of the l^{th} SCR user and is defined as $\zeta_{r_l} = \frac{\zeta_{s_l} \sigma^2_{h_l^{(r)}}}{\sigma^2_{w_{c_l}}}$. In the assumed CR network, it is considered that the end-to-end SNR between the AU and the merging point remains the same. This implies that $\zeta_l = \zeta = \frac{\zeta_r \zeta_s \sigma^2_w}{\zeta_r \sigma^2_w + \zeta_s}$, where $l \in \{1, 2, .., L\}$. Here, $\zeta_{s_l} = \zeta_s$, $\zeta_{r_l} = \zeta_r$, and $\sigma^2_{w_l} = \sigma^2_w$. To attain a final decision, CED is implemented at the end of each SCR user. Thus, we calculate $|z_{c,l}|^2$ by utilizing the reported observation from the l^{th} SCR user over the faulty control channel. At the merging point, the reported observations from the L SCR users undergoes selection combining to determine the final decision regarding hypotheses $\mathcal{H}_0$ or $\mathcal{H}_1$.

III. PERFORMANCE EVALUATION OF THE PROPOSED CR NETWORK

Using the SSI fusion rule, the test statistic at the merging point can be expressed as follows:

$$W \underset{\mathcal{H}_0}{\overset{\mathcal{H}_1}{\gtrless}} \beta, \quad (3)$$

where $W = max\left(|z_{c,1}|^2, |z_{c,2}|^2, ... |z_{c,L}|^2\right)$, β is the SSI fusion's threshold. Under both hypotheses $\mathcal{H}_0$ and $\mathcal{H}1$, we make the assumption that the $z_{c,l}$ values at different SCR users are conditionally independent. The probability density function (PDF) of W under $\mathcal{H}_0$, considering the sensing and control channels as known, can be expressed as:

$$f_{W|\mathcal{H}_0}(L, z) = L\, e^{-z} \left(1 - e^{-z}\right)^{L-1}, \quad (4)$$

likewise, PDF of W in equation (3) under $\mathcal{H}_1$ as follows:

$$f_{W|\mathcal{H}_1}(L, z, \beta) = \frac{L}{\zeta+1}\, e^{-\frac{z}{\zeta+1}} \left(1 - e^{-\frac{z}{\zeta+1}}\right)^{L-1}. \quad (5)$$

In the following section, we will present the closed-form expression for the false-alarm probability and the missed-detection probability of a CR network with CED using the SSI fusion rule.

Theorem 1. *The false-alarm probability and the missed-detection probability for a CR network with CED, employing the SSI fusion rule, can be expressed as follows:*

$$Z_F(L, \beta) = 1 - \left(1 - e^{-\beta}\right)^L, \quad (6)$$

$$Z_M(L, \beta, \zeta) = \left(1 - e^{-\frac{\beta}{\zeta+1}}\right)^L. \quad (7)$$

Proof. Please see Appendix I. □

Special scenario

- When $L = 1$, The false alarm and missed detection probability for the proposed CR network is given by

$$Z_F(1, \beta) = e^{-\beta}, \quad (8)$$

$$Z_M(1, \beta, \zeta) = 1 - e^{-\frac{\beta}{\zeta+1}}. \quad (9)$$

IV. PROBLEM FORMULATION

The accuracy of sensing at the merging point is quantified using the average error rate, which is given by the equation $\Theta Z_F(L, \beta) + (1 - \Theta) Z_M(L, \beta, \zeta)$. Here, Θ represents the probability of $\mathcal{H}_0$ as defined in the [15]. Our objective is to formulate the optimal selective soft-information fusion (SSFP) for a CR network in the presence of faulty control channels. The objective of the SSFP is to minimize the average error rate at the merging point. The optimization variables involved in SSFP are denoted as β and L.

$$\text{SSFP:} \quad \min_{\beta, L} \quad \Theta Z_F(L, \beta) + (1 - \Theta) Z_M(L, \beta, \zeta). \qquad \text{s.t.} \quad L \geq 1, \beta > 0 \quad (10)$$

V. Optimization of the CR Network Using the SSI Fusion Rule

A. Optimization of SSI Fusion's Threshold (β)

To determine the optimal value of β for a given L, we can calculate the first-order partial derivative of the objective function stated in equation (10) with respect to β. Equating this derivative to zero yields the mathematical expression as follows:

$$\frac{\partial Z_E\left(L,\beta,\zeta\right)}{\partial\beta}=0. \tag{11}$$

Equation (11) implies

$$\Theta\frac{\partial Z_F\left(L,\beta\right)}{\partial\beta}+\left(1-\Theta\right)\frac{\partial Z_M\left(L,\beta,\zeta\right)}{\partial\beta}=0. \tag{12}$$

The first-order partial derivatives of equations (6) and (7) with respect to β can be expressed as follows:

$$\frac{\partial Z_F\left(L,\beta\right)}{\partial\beta}=-\,L\;e^{-\beta}\left(1-e^{-\beta}\right)^{L-1}, \tag{13}$$

$$\frac{\partial Z_M\left(L,\beta,\zeta\right)}{\partial\alpha}=\frac{L}{\zeta+1}\;e^{-\frac{\beta}{\zeta+1}}\left(1-e^{-\frac{\beta}{\zeta+1}}\right)^{L-1}. \tag{14}$$

By substituting (13) and (14) into (12), we can numerically calculate the optimal value of β.

B. Optimization of SCR users (L)

Though cooperative spectrum sensing can enhance sensing performance, it introduces additional overhead at the merging point. To mitigate this overhead, we focus on optimizing the SCR users within a CR network.

Lemma 1. *The optimal value of L, denoted as $L^*(\beta,\zeta)$, which minimizes objective function in* (10)*, can be expressed as follows:*

$$L^*(\beta,\zeta)=\left\lceil\frac{ln\left(\frac{1-\Gamma_1}{1-\Gamma_2}\right)}{ln\left(\frac{\Gamma_2}{\Gamma_1}\right)}\right\rceil, \tag{15}$$

here, $\lceil.\rceil$ represents the ceiling function, $\Gamma_1=1-e^{-\frac{\beta}{\zeta+1}}$ and $\Gamma_2=1-e^{-\beta}$.

Proof. Please see Appendix II. □

VI. Numerical Results

Under the given assumptions, we proceed to calculate the numerical results for the proposed CR network using the SSI fusion rule. Here are the values for the given parameters: $\Theta=1/2$, $\sigma^2_{w_l}=\sigma^2_{w_{c,l}}=1$, $\zeta_{r_l}=\zeta_r=10$ dB, where $l\in\{1,2,.....,L\}$.

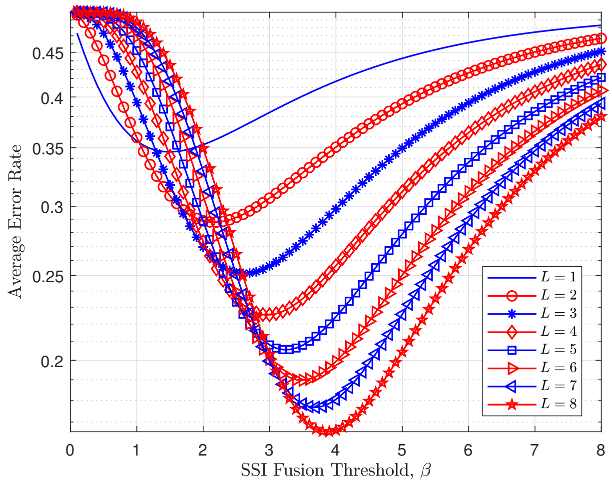

Fig. 2. Average error rate versus β for the proposed CR network using the SSI fusion rule for various values of L, $\zeta_s=2$ dB.

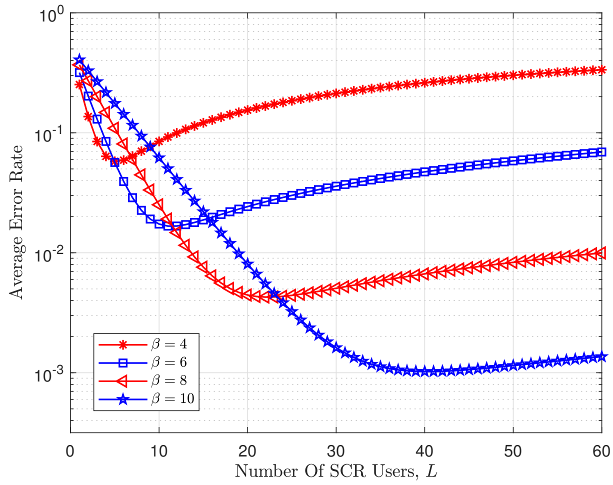

Fig. 3. Average error rate versus L for the proposed CR network using the SSI fusion rule for various β values, $\zeta_s=10$ dB.

Fig.2 illustrates the relationship between the average error rate and β for different values of L. The plot demonstrates that, when L is fixed, the average error rate displays a convex pattern with respect to β. Additionally, for each L value, there exists a particular range of β values that leads to a lower average error rate. This observation indicates the presence of an optimal L value for any given β, where the average error rate is minimized. Similarly, Fig.3 showcases the convex behavior of the average error rate with respect to L. This finding implies that for each specific value of β, there exists an optimal L value that minimizes the average error rate.

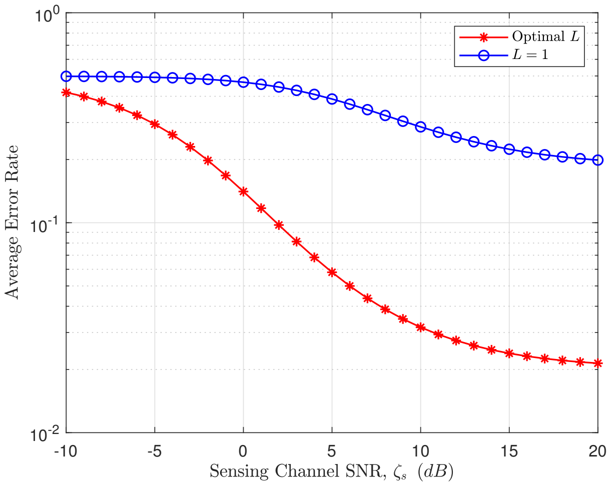

Fig. 4. Average error rate versus ζ_s for $\beta = 5$

Fig.4 shows the performance of the CR network using the SSI fusion rule in terms of the average error rate, considering optimal values of L and $L = 1$. Fig.4 clearly demonstrates that the proposed CR network, employing the SSI fusion rule with optimal values of L, exhibits better performance compared to the CR network with L=1. The reason for the improved performance of the proposed CR network with optimal values of L is that spectrum sensing conducted by multiple CR users yields a lower average error rate compared to single-user spectrum sensing ($L = 1$).

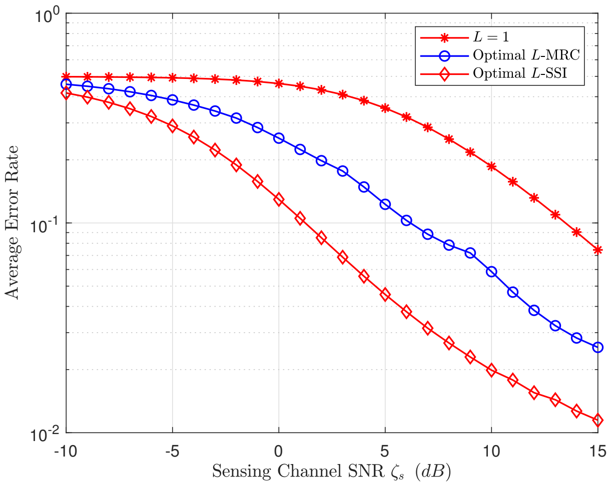

Fig. 5. Average error rate versus ζ_s in dB at $\beta = 5$, Optimal L.

Fig.5 illustrates a comparison between the average error rates of the proposed CR network, employing the SSI fusion rule, and an existing MRC fusion scheme from the literature. In Fig.5, the control channels (ζ_r) are assumed to be error-free. The plots in Fig.5 compare the average error rates of the proposed CR network with SSI fusion rule with the existing MRC scheme mentioned in [15]. The comparison with the state-of-the-art is conducted for the optimal values of parameter L. From Fig.5, it is evident that the proposed CR network, which incorporates the SSI fusion rule with optimized values of L, outperforms the CR network utilizing MRC implemented in existing literature [15]. The numerical results make it clear that the proposed CR network, which utilizes the SSI fusion rule, offers significantly improved sensing accuracy compared to the existing CR network that relies on MRC.

VII. Conclusions

In this paper, we examined the CSS scheme using CED and SSI fusion rules over faulty control channels. Additionally, we derived closed-form expressions for the probability of false-alarm and missed-detection. The proposed CR network's performance utilizing the SSI fusion rule is compared with various combining schemes that have been implemented in existing literature. The numerical results show that the former exhibits more reliable spectrum sensing compared to the latter.

Appendix I: Proof of Theorem 1

The probability of a false alarm at the merging point can be calculated using (3) and (4) as given below:

$$\begin{aligned} Z_F(L,\beta) &= \Pr(W > \beta|\mathcal{H}_0) \\ &= \int_\beta^\infty f_{W|\mathcal{H}_0}(L,z)\,dz \\ &= \int_\beta^\infty L\,e^{-z}\left(1-e^{-z}\right)^{L-1}dz \\ &= 1-\left(1-e^{-\beta}\right)^L, \end{aligned} \tag{16}$$

where (16) can be expressed as

$$Z_F(L,\beta) = 1-\left(1-e^{-\beta}\right)^L.$$

The missed detection probability at the merging point can be represented by using (3) and (5) as follows:

$$\begin{aligned} Z_M(L,\beta,\zeta) &= \Pr(W < \beta|\mathcal{H}_1) \\ &= \int_0^\beta f_{W|\mathcal{H}_1}(L,z,\zeta)\,dz \\ &= \int_0^\beta \frac{L}{\zeta+1}\,e^{-\frac{z}{\zeta+1}}\left(1-e^{-\frac{z}{\zeta+1}}\right)^{L-1}dz \\ &= \left(1-e^{-\frac{\beta}{\zeta+1}}\right)^L, \end{aligned} \tag{17}$$

We can write (17) as

$$Z_M(L,\beta,\zeta) = \left(1-e^{-\frac{\beta}{\zeta+1}}\right)^L.$$

Appendix II: Proof of Lemma 1

$$\begin{aligned} &\Theta\left[Z_F(L+1,\beta)-Z_F(L,\beta)\right]+(1-\Theta) \\ &\times\left[Z_M(L+1,\beta,\zeta)-Z_M(L,\beta,\zeta)\right]\geq 0, \end{aligned} \tag{18}$$

and

$$\Theta \left[Z_F\left(L,\beta\right) - Z_F\left(L-1,\beta\right)\right] + \left(1-\Theta\right) \times \left[Z_M\left(L,\beta,\zeta\right) - Z_M\left(L-1,\beta,\zeta\right)\right] < 0. \tag{19}$$

By satisfying (18) (or) (19) given by, we can get the optimal value of L, denoted as $L^*(\beta,\zeta)$, that minimizes the objective function in (10) with the assumption $\Theta = \frac{1}{2}$.

From (6) and (7), we obtain

$$Z_F\left(L+1,\beta\right) - Z_F\left(L,\beta\right) = e^{-\beta}\left(1-e^{-\beta}\right)^L, \tag{20}$$

$$Z_M\left(L+1,\beta,\zeta\right) - Z_M\left(L,\beta,\zeta\right) = e^{-\frac{\beta}{\zeta+1}}\left(1-e^{-\frac{\beta}{\zeta+1}}\right)^L. \tag{21}$$

Substituting (20) and (21) in (18), we obtain the optimal value of L as follows:

$$L^*(\beta,\zeta) = \left\lceil \frac{ln\left(\frac{1-\Gamma_1}{1-\Gamma_2}\right)}{ln\left(\frac{\Gamma_2}{\Gamma_1}\right)} \right\rceil.$$

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