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An LLR Based Cooperative Spectrum Sensing with Hard-Soft Combining for Cognitive Radio Networks

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Abstract

In cognitive radio networks, cooperative spectrum sensing schemes improve the reliability of the detection by exploiting decisions made locally by several secondary users (SUs). Soft energy combining schemes provide optimal detection performance by combining the actual sensed information from the SUs, resulting in high cooperation overhead in terms of time, computational complexity, and bandwidth. Alternatively, hard energy combining schemes offer lower cooperation overhead, but provides sub-optimal detection performance. In this paper, a log-likelihood ratio (LLR) based cooperative spectrum sensing scheme with hard-soft combining at fusion centre (FC)is proposed, where the SUs perform a local LLR based detection employing two thresholds. If the locally sensed informations falls in between the two threshold values, then the actual sensed information is reported to the FC and weighted soft combining is performed at FC, else the local binary decisions are reported to FC and hard combining is performed. Further, a second stage hard combining employing AND/OR rule is performed at FC considering the previous decisions. The performance evaluation through simulation shows that the proposed scheme gives the near optimal performance with a slight increase in cooperation overhead.

1 Introduction

In modern wireless communication systems, the demand for the RF spectrum is constantly increasing, leading to scarcity of spectrum resources [1, 2]. The cognitive radio (CR) technology [3], a candidate for upcoming 5G communication systems [4], promises to overcome the spectrum scarcity problem by allowing the secondary users (SUs) to dinamically access a licensed band, when the licenced band or primary users (PUs) are absent/idle [3, 5, 6]. To enable dynamic spectrum access, SUs should have precise and reliable detection of the available spectrum spaces [6]. The sensitivity of spectrum sensing depends on many channel impairments like multipath fading, pathloss, interference and receiver uncertainty [7, 8]. Therefore, the reliability of decision can be enhanced by making the cooperation among the SUs present at a femto cell like scenario [5].

Cooperative spectrum sensing in cognitive radio network (CRN) exploits spatial diversity by combining the sensing data provided by multiple SUs in an efficient manner at the fusion center (FC) [5]. In hard combining schemes, each SU performs local spectrum sensing and sends its decision (on presence or absence of PU) as a one bit information (0 or 1) to the FC, and FC combines those results to make the final decision. In soft combining schemes, the observed energy of SUs are reported to the FC and FC combines those information with some optimal coefficients/weights and makes decisions about the presence or absence of the PU signal depending on a threshold. These coefficients are related to instantaneous signal-to-noise ratio (SNR) of SUs. There are few important combining schemes viz. Equal Gain Combining (EGC) [9], Weighted Linear Combining (WLC) [10], and Optimal Combining (OC) [11]. A log-likelihood ratio (LLR) based cooperative spectrum sensing is reported in [7], where a two threshold based detection of PU signal is performed, in which, processing overhead and channel bandwidth requirements are reduced as SUs send only the local sensed results, not the observed information. The uncertain sensing results falling in between the two thresholds is simply dropped at the local SUs resulting in performance degradation. In this work, this problem has been resolved by sending the actual sensing information to the FC for uncertain sensing results. In FC, the weighted combination of the decisions reported by SUs is performed [10] and the instantaneous weight vector is estimated considering only the sensing channel SNR, but the reporting channel SNR has not been taken into consideration which leads to the decrease of the reliability of the decision. In this research, the weight vector is estimated by considering both the sensing channel and the reporting channel SNRs as represented in Fig. 1.

In this paper, we have proposed an LLR based cooperative spectrum sensing with hard-soft combining at FC. In the proposed cooperative sensing scheme, first a local LLR based detection by employing two threshold values is performed at the SUs. The local decisions, which fall in between the two threshold values, can be called as uncertain sensing results. The actual observed information are reported to the FC by SUs whenever they get uncertain sensing results. Further, a weighted soft combining is performed with the actual sensed data at FC. In rest of the cases, where local sensing results fall in decisive region as depicted in Fig. 2, are directly transmitted to the FC and hard combining is performed by accumulating those binary decisions. Further, FC makes the second stage hard combining employing logical AND/OR rule considering both the decisions, which came from the previous soft and hard combining stages. Performance evaluation through simulation shows that the proposed LLR based cooperative spectrum sensing with hard-soft combining gives a ROC plot very close to optimal soft combining performance with a slight increase in sensing overhead compared to that of the hard combining at FC. Intuitively it could be observed that the chances of uncertain sensing results at SUs is very small, hence the increase in the sensing overhead owing to the transmission of actual sensed data is also very small. Moreover, in this work, the instantaneous weight vector for combining is estimated considering both the sensing channel and reporting channel SNRs, which enhances the reliability of the detection at FC. It is worthy to note that overhead caused by reporting the estimated sensing channel SNR to FC is alleviated as estimation is performed only after some *n* number of sensing intervals (SI).

In the next section, the system architecture of the CRN is described

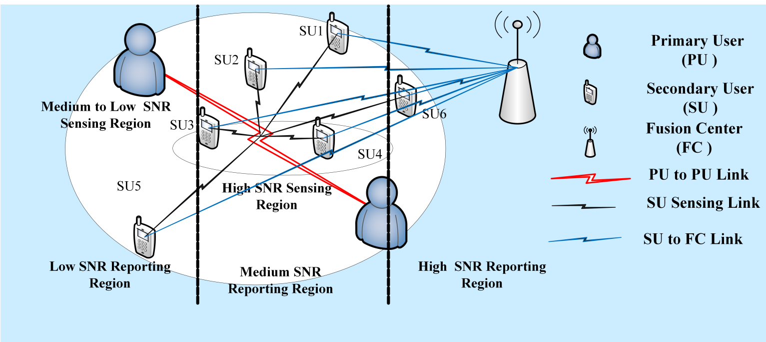

Figure 1. System model for cooperative spectrum sensing

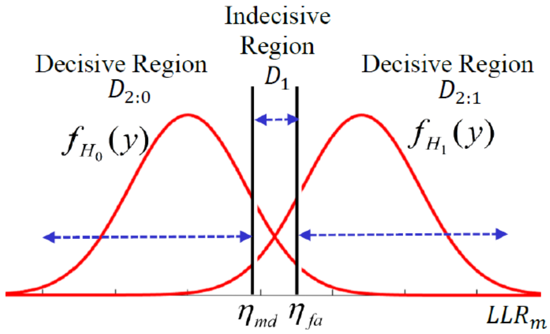

Figure 2. Binary hypothesis testing

and problem statement is presented. In section 3, LLR based cooperative spectrum sensing with hard-soft combining is proposed. The detail study on performance evaluation through simulation is presented in section 4 and some concluding remarks have been made in the succeeding section.

2 System model

A network scenario with a conceptual representation of our purposed scheme is presented in Fig. 1, where six SUs are trying to sense the link between PUs and make their local decision using LLR based detection. Further, the decisions are reported to the FC that makes the global decision. At each SU, an LLR based statistical hypothesis testing is performed to detect the presence of the PU signal. The binary hypothesises H_0 and H_1 represent the absence and presence of the PU signal respectively. The third hypothesis H_2 which represents the uncertain sensing of PU signal in the indecisive region. The binary hypothesis testing is represented in Fig .2 and is defined as:

H_0 : PU is absent,
H_1 : PU is present,
H_2 : Ambiguity about the presence of PU.

In the proposed system model, the signal received by the m^{th} SU is given by

$$H_0 : r_m[k] = n_m[k], \tag{1}$$
$$H_1 : r_m[k] = \alpha_m s[k] + n_m[k], \tag{2}$$

and the uncertain hypothesis of the PU detection by the m^{th} SU is given by

$$H_2 : r_m[k] = \phi\alpha_m s[k] + n_m[k], \tag{3}$$

where $m = 1,2,...,M$; and $k = 1,2,...,K$, such that, M is the number of SUs and K is the total number of samples considered for the detection. $n_m[k]_1^K$ represents the additive noise samples that are gaussian i.i.d ($\mathcal{N}(0,\sigma_n^2)$). $s[k]_1^K$ represents the PU signal samples that are deterministic and unknown. The combined effect of fading and path loss on the PU signal that is received by the m^{th} SU is represented by a complex variable α_m is also unknown. Therefore, there are three unknown parameters: the noise variance (σ_n^2), signal data information ($s[k]_1^K$), and wireless channel effect (α_m) experienced by a particular SU_m and ϕ is the uncertainty factor which can have a value '0' or '1' for the decision to fall in non-deterministic region. Assuming the channel conditions to remain constant for a sensing interval (K samples), the received energy E_m for the m^{th} SU can be represented as [10]:

$$E_m = \sum_{k=1}^{K} |r_m[k]|^2. \tag{4}$$

Let the sensing data of all SUs are i.i.d, so the pdf of received signal for all the three hypothesis using central limit theorem can be approximated as [12]:

$$H_0 : E_m \sim P_{0,m}(r_m[k])$$
$$E_m \sim \mathcal{N}(k\sigma_n^2, k\sigma_n^4), \tag{5}$$
$$H_1 : E_m \sim P_{1,m}(r_m[k])$$
$$E_m \sim \mathcal{N}(k(1+\gamma_m)\sigma_n^2, k(1+2\gamma_m)\sigma_n^4), \tag{6}$$

and,

$$H_2 : E_m \sim P_{2,m}(r_m[k])$$
$$E_m \sim \mathcal{N}(k(1+\rho_m)\sigma_n^2, k(1+2\rho_m)\sigma_n^4). \tag{7}$$

Assuming the PU signals as BPSK modulated and E_s be the symbol energy of PU, then the SNR value experienced by m^{th} SU for the hypothesis H_1 and H_2 is given by [12],

$$\gamma_m = \frac{E_s|\alpha_m|^2}{\sigma_n^2} \text{ and } \rho_m = \frac{E_s|\phi\alpha_m|^2}{\sigma_n^2}. \tag{8}$$

The probability distribution has two unknown variables α_m and σ_n, which are the unkown primary signal SNR parameters, used for composite hypothesis testing and they can be estimated as proposed in [13].

In spectrum sensing, the probability of detection (P_d) and the probability of false alarm (P_{fa}) are two important metrics, that are used to evaluate the performance of the detection scheme. For efficient spectrum utilization, P_{fa} should be as small as possible. On the other hand, the increase in probability of miss detection ($P_{md} = 1 - P_d$) increases the undesired interference between the SUs and the PU. There is a *trade-off* between P_{fa} and P_{md} and the goal of a detection scheme is to enhance the P_d for an acceptable value of P_{fa}. For the present detection problem under consideration represented in Fig. 2, the probabilities are defined as follows,

$$P_d = P(D_{2:1}|H_1) = f_{H_1}(y) > \eta_{fa} : H_1, \tag{9}$$

$$P_{fa} = P(D_{2:0}|H_0) = f_{H_0}(y) > \eta_{fa} : H_0, \tag{10}$$

and

$$P_{md} = P(D_{2:0}|H_1) = f_{H_1}(y) < \eta_{md} : H_1. \tag{11}$$

3 Proposed LLR Based Cooperative sensing with Hard-Soft Combining

In cooperative spectrum sensing, the energy samples of PU signal are either used by SUs for local sensing or could be used by FC, depending on the selected combining scheme. In WLC, SNR dependent weight is considered at the FC for energy combining and represented as follows,

$$\sum_{m=1}^{M} w_m E_m \underset{H_0}{\overset{H_1}{\gtrless}} \eta_{WLC}, \tag{12}$$

where, $w_m = \frac{\gamma_m}{1+2\gamma_m}$.

In hard combining techniques, the detection performance is suboptimal due to the loss of information at the FC. In [7], an LLR based cooperative spectrum sensing employing two threshold levels is proposed, where, each SU performs a LLR based sensing to detect the presence of PU signal. The LLR expression for m^{th} SU is given by

$$LLRm = ln\left(\prod_{k=1}^{K}\frac{P_{1,m}(r_m[k])}{P_{0,m}(r_m[k])}\right) = \sum_{k=1}^{K} ln\left(\frac{P_{1,m}(r_m[k])}{P_{0,m}(r_m[k])}\right),$$

$$= \sum_{k=1}^{K} ln\left(\frac{\frac{1}{\sqrt{2pi\sigma_n^2}}exp\left(-\frac{|r_m[k]-\alpha_m s[k]|^2}{2\sigma_n^2}\right)}{\frac{1}{\sqrt{2pi\sigma_n^2}}exp\left(-\frac{|r_m[k]|^2}{2\sigma_n^2}\right)}\right). \tag{13}$$

The local binary hypothesis testing result of each SU L_m using two threshold values can be expressed as,

$$L_m = \begin{cases} -1 & LLR_m \leq \eta_{md} \text{ or } H_0 \\ +1 & LLR_m \geq \eta_{fa} \text{ or } H_1 \\ 0 & \eta_{md} < LLR_m < \eta_{fa} \text{ or } H_2. \end{cases} \tag{14}$$

The threshold level η_{md} and η_{fa} can be determined for a fixed value of probability of false alarm P_{fa} and probability of missed detection P_{md} and given in [7] as,

$$\eta_{fa} = ln\left(\frac{1-P_{md}}{P_{fa}}\right), \text{ and } \eta_{md} = ln\left(\frac{P_{md}}{1-P_{fa}}\right). \tag{15}$$

Further, the sensing results obtained from SUs are combined at FC for each sensing interval. FC performs a binary hypothesis testing of the combined result to find the presence or absence of the PU signal. In [7], the local decisions, which fall in the region between two threshold levels i.e η_{md} and η_{fa} , are discarded resulting in performance degradation. In this paper, we have proposed a two stage combining scheme at FC. In this scheme, the actual sensed energy sample of the PU signal is transmitted to FC when it falls in the indecisive region. FC, then combines the energy samples obtained from from the SUs with uncertain sensing result using WLC scheme as represented in equ.(18). On the other hand, the SUs transmit binary decisions to the FC, when the sensed data falls in the decisive region, and FC combines them. In the second phase of combining, FC combines both the decisions came from the previous hard and soft combining phases using AND/Or rule.

In the first phase, the decision is made with soft combining scheme for the indecisive sensing results of secondary users, and can be expressed as,

$$D_1 = \sum_{p=1}^{P} w_p E_m \underset{H_0}{\overset{H_1}{\gtrless}} \eta_{WLC}, \tag{16}$$

where, P is the total number of SUs whose results fall in indecisive region , $w_p = \frac{2\gamma_p\gamma_p'}{1+2\gamma_p\gamma_p'}$; where, γ_p is the estimated sensing channel SNR at the p^{th} SU, and γ_p' is the reporting channel SNR from p^{th} SU to FC. Further weight factor can be improved by using trust based algorithm. Next, the decision D_2 is made by combining the binary decisions obtained from the SUs who got decisive sensing binary results and expressed as follows,

$$D_2 = \sum_{q=1}^{M-P} L_m \underset{H_0}{\overset{H_1}{\gtrless}} 0. \tag{17}$$

The decision results D_1 and D_2, obtained from the first phase of combining, are further combined at FC using AND rule or OR rule and can be mathematically expressed as follows,

$$D = D_1 * D_2, \text{ and } D = D_1 || D_2. \tag{18}$$

In this research, instead of estimating the sensing channel SNR and reporting channel SNR after each SI, we are estimating the SNR after a certain number of SIs by exploiting the correlation of wireless channel. Thus, the high processing overhead occurred in WLC and OC techniques could be alleviated. The simulation results in the next section will show the proposed technique has detection performance no worse than the detection performance of the schemes where SNR is estimated after each SI. Unlike the WLC and OC techniques, the proposed scheme suffers from only one bit overhead when the hard decisions are sent to the FC. However, the schemes suffers from K bit overhead, when soft information are sent to FC. Intuitively it could be observed that the chances of uncertain sensing results at SUs is very small, hence the increase in the sensing overhead owing to the transmission of actual sensed data is also very less. It is worthy to note that, in the proposed sensing scheme, the total processing overhead due to weight estimation is distributed among SUs and FC as the instantaneous weight vector corresponding to the sensing channel SNR is estimated at SUs and the weight vector corresponding to the reporting channel SNR is computed at FC. therefore, the proposed scheme enables longer battery life for both the SUs and FC. Hence we believe that the proposed scheme provides a practical and reliable solution with low cooperation overhead to enable efficient spectrum utilization for next generation 5G networks.

4 Performance evaluation through simulation

To evaluate the performance of the proposed scheme, we consider a LTE like femto-cell CRN with a established PU link and with M number of SUs, which are distributed randomly in an area of $100\ X\ 100\ sq.m.$ as depicted in Fig. 1. The SUs are mobile, but in a particular sensing interval it is static and the sensed energy samples of PU link at each SU are affected by fading and path loss, which are time varying in nature. We have also considered a very poor SNR scenario to test the reliability of the proposed scheme. we consider that the PU transmits BPSK modulated signal at a 500kbps rate. The number of samples used for parameter estimation (K) and for LLR are 500 and 20 samples, respectively. The initial values of α_m^p and σ_m^p are taken as 0.5 and 1+1j respectively and the values for E_s, M, P_{fa} and P_{md} are taken as 1, 6, 0.01, and 0.02 respectively.

The detection performance of the proposed scheme is compared with optimal LLR based soft combining , LLR based hard combining [7], and with equal gain combining schemes [9], as depicted in Fig. 3- Fig. 5. Fig. 3 depicts the P_d vs. SNR plot for a fixed value of $P_{fa} = 0.01$. Fig. 3 clearly shows that the proposed LLR based cooperative sensing with hard-soft combining gives a near optimal performance even at a very poor SNR $= -6\ dB$ and outperforms all hard combining schemes and EGC at each SNR level. It also shows that the proposed logical OR-based hard-soft combining gives a better result compare to AND operation. ROC plot of the various combining schemes is presented in Fig. 4, for a fixed value of SNR $= 6\ dB$. Fig. 4 clearly shows that the proposed LLR based sensing with hard-soft combining gives a near optimal performance when very small values of P_{fa} and P_{md} are selected then the indecisive region gets larger, where the proposed scheme gives a near optimal result unlike the LLR based hard combining scheme. As, discussed in the previous section, there will be slight increase of sensing overhead owing to the transmission of actual sensed data to the FC for uncertain sensing in SUs. But, the overhead is very small as the chance of falling the sensed information in indecisive region is also small. Fig. 5 gives a SU vs. P_d plot, which shows that the detection

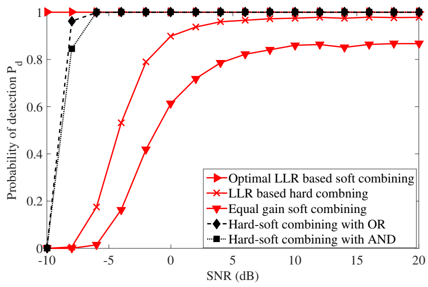

Figure 3. Probability of detection P_d vs. SNR plot

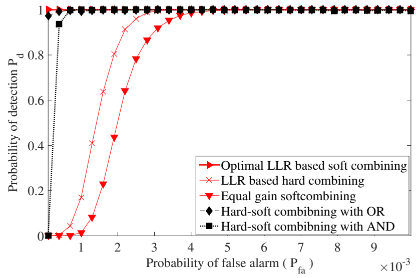

Figure 4. ROC plot of cooperative spectrum sensing

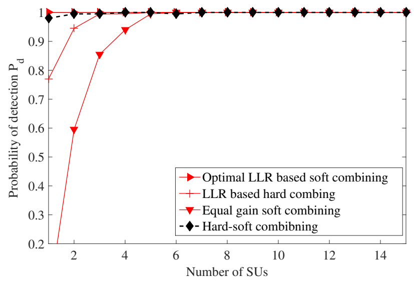

Figure 5. Probability of detection P_d vs. number of SUs

performance improves for all the spectrum sensing schemes when the number of cooperating SUs is increased. It also shows that the performance of proposed scheme is very good even with a small number of SUs $= 2$, which proves the reliability of the proposed sensing scheme.

5 Conclusion

In this paper, an LLR based cooperative spectrum sensing with hard-soft combining is proposed, in which uncertain local sensing results are reported to FC to enhance the detection performance with a slight increase in sensing overhead. Next, FC performs two phase combining, where in first phase weighted soft combining is done with the actual sensed data corresponding to the indecisive region and hard combining with LLR is done corresponding to the decisive region. In the next phase of combining, FC combines the decisions, came from the previous stage, employing AND/OR rule. Further, in this work the instantaneous weight vector is estimated considering both the sensing channel and reporting channel SNRs, that enhances the reliability of the detection scheme. The simulation results show that the proposed detection scheme gives a near optimal performance when compared to the optimal soft energy combining schemes and the LLR based sub-optimal hard combining scheme. In future, this work could be extended for MIMO channels and in full-duplex scenarios.

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