Performance analysis of data fusion schemes in cooperative spectrum sensing for cognitive radio networks

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Abstract—In the actual communication environment, the accuracy of spectrum detection is easily affected by the uncertainty factors such as multipath fading, shadow effect, hidden terminal, channel signal-to-noise ratio, and noise variance fluctuation. Cooperative spectrum sensing technology makes full use of the spatial gain generated by sensor nodes in different geographical locations, and obtains more accurate combination decision results than single node decision. In cooperative sensing, fusion center (FC) will analyze and process the collected local detection statistics or sensing results according to a certain data fusion rule, and make the final decision on the current channel state according to the fusion results. Data fusion strategy plays an important role in perception results and system reliability. In this paper, we summarize several conventional data fusion schemes in cooperative spectrum sensing for cognitive radio networks and conduct performance analysis.

1. INTRODUCTION (HEADING 1)
In cognitive radio system, due to the limitations of hardware conditions and signal processing ability of cognitive nodes, it is difficult for a single secondary user (SU) to achieve the accuracy of detection results in the unsatisfactory physical environment [1]. Especially, the accuracy of spectrum detection is easily affected by uncertainties such as multipath fading, shadow effect, hidden terminal and noise variance fluctuation.

By sharing the spectrum sensing information, the SUs distributed in different locations of the network can make more accurate combination decision than single node decision. In addition, under the requirement of system detection, the cooperative spectrum sensing nodes need shorter sensing time and sampling period, so that the proportion of effective data in the data frame structure is higher, and spectrum sensing can obtain higher throughput than single node [2]. However, the transmission of sensing data, the allocation of reporting channels, and the coordination between nodes will also bring certain profits and losses. Excessive data delay will also lead to the failure of decision-making results, and the channel allocation strategy can not be adjusted timely according to the use of authorized frequency band, resulting in conflicts or interference [3]. Therefore, cooperative spectrum sensing needs to comprehensively measure the gain and loss from multiple perspectives, optimize the sensing strategy and cooperation mode, and minimize the impact of the additional overhead on the system.
2. System model

2.1. Energy detection method

Energy detection is a typical spectrum sensing technology, and is widely used due to the characteristics of complexity and fast detection [4]. By pre-filtering and ADC processing, the energy value will be accumulated. Then, compared with the pre-set threshold, the status of Primary user (PU) can be determined. The detection statistics can be expressed as follows:

\[ T = \sum_{n=0}^{N-1} x^2(n), \]  

(1)

where \( x(n) \) denotes the discrete sequence of signals collected in a period of time, and \( N \) is the number of sampling points.

The distribution of detection statistics is as follows

\[ T : \begin{cases} \chi^2_{2N}, & H_0 \\ \chi^2_{2N}(2\gamma), & H_1 \end{cases} \]  

(2)

where \( \gamma \) is the signal-to-noise ratio and \( \chi^2_{2N}(\gamma) \) is the central chi square distribution of degree of freedom \( 2N \). Besides, \( \chi^2_{2N}(\gamma) \) is the non-central chi square distribution of degrees of freedom \( 2N \), and its decentralization parameter is \( 2\gamma \).

Because of its low complexity and no prior information about PU, the energy detection method is suitable for cognitive user nodes with poor processing capacity [5]. However, under the condition of low signal-to-noise ratio, the performance is not sensitive enough, and the detection performance will be greatly different due to the uncertainty of noise. According to the different types of data uploaded by SUs, the fusion strategies can be divided into hard fusion and soft fusion. In the hard fusion, the node makes local decision according to the sensing information and generates a bit result. FC obtains the global decision result by using certain combine criteria [6]. Comparatively, during soft fusion process, the sensing node will upload the original information directly instead of local decision.

2.2. Hard fusion

(1) K-out-of-N rule

K-out-of-N rule is known as majority criterion. If the number of nodes participating in cooperative sensing is set as \( N \), FC can decide whether to occupy the channel state of authorized users only if the number of nodes giving consistent decision is not less than \( K \). Hence, the decision of k-out-of-n criterion can be given by [7]:

\[ \begin{cases} \sum_{i=1}^{N} d_i \geq K, & H_1 \\ \sum_{i=1}^{N} d_i < K, & H_0 \end{cases} \]  

(3)

where \( d_i \) represents the local sensing result of the \( i \)-th SU.

Thus, the global detection probability and global false alarm probability of the k-out-of-n criterion can be expressed as follows:

\[ P_{d,\text{majority}} = \sum_{j=K}^{N} \sum_{d_{\neg j}=1}^{N} \prod_{i=1}^{N} (p_{d,i})^j (1-p_{d,i})^{1-d_j}, \]  

(4)

\[ P_{f,\text{majority}} = \sum_{j=K}^{N} \sum_{d_{\neg j}=1}^{N} \prod_{i=1}^{N} (p_{f,i})^j (1-p_{f,i})^{1-d_j}. \]  

(5)

(2) OR rule

By employing OR rule, only when all SUs decide that PU does not exist, the final decision result demonstrates that the channel is available. And the global detection probability and global false alarm probability can be given, respectively, by
\begin{align}
P_{d,aw} & = 1 - \prod_{i=1}^{N}(1 - p_{d,i}) , \quad (6) \\
P_{f,aw} & = 1 - \prod_{i=1}^{N}(1 - p_{f,i}) . \quad (7)
\end{align}

(3) AND rule

And rule means that if there is at least one local decision result about PU does not exist, the final decision approves that the authorized channel is available. Then, the corresponding global detection probability and global false alarm probability can be given, respectively, by
\begin{align}
P_{d,\text{and}} & = \prod_{i=1}^{N} p_{d,i} , \quad (8) \\
P_{f,\text{and}} & = \prod_{i=1}^{N} p_{f,i} . \quad (9)
\end{align}

And rule can obtain low false alarm probability, but its detection probability is too low. Unless the signal-to-noise ratio of SUs is large, the satisfactory sensing performance can be obtained.

2.3. Soft fusion

In soft data fusion, the SUs forward the whole sensing results to FC for fusion without any local decision, and make decisions by combing these sensing data in FC by using appropriate fusion algorithm [9]. Due to the relatively high computational complexity and large amount of data transferred, the soft fusion scheme needs more system overhead than the hard fusion scheme. The combining methods of soft fusion include: square law combining (SLC) [9], maximum ratio combining (MRC) [10] and square law selection (SLS) [11].

(1) SLC

In SLC, the estimated energy of each SU will be sent to the FC, and then be added. The sum will be compared with the threshold and determine whether PU exists or not, which can be defined as:
\[ E_{SLC} = \sum_{i=1}^{N} E_{i} , \quad (10) \]
where \( E_{i} \) represents the detection statistic of the \( i \)-th SU.

On AWGN channel, the detection probability and false alarm probability of the scheme are as follows:
\begin{align}
P_{d,SLC} & = Q_{\alpha} \left( \sqrt{2 \gamma_{SLC} \lambda} \right) , \quad (11) \\
P_{f,SLC} & = \frac{\Gamma \left( Nu, \frac{\lambda}{2 \sigma^2} \right) \Gamma(Nu)}{\Gamma(Nu)} . \quad (12)
\end{align}

where \( \lambda \) denotes the decision threshold, \( u \) is the time bandwidth product, \( \sigma^2 \) is the long-term average noise variance, and \( Q_{\alpha}(.) \) is the generalized Marcum Q-function. Besides, \( \Gamma(.) \) and \( \Gamma(.) \) are the incomplete gamma function and the complete gamma function respectively. In addition, \( \gamma_{SLC} \) is defined as:
\[ \gamma_{SLC} = \sum_{i=1}^{N} \lambda_{i} , \quad (13) \]
where \( \lambda_{i} \) is the primary user SNR perceived by \( i \)-th SU.

(2) MRC

In SLC, the energy received by each user in the FC is normalized and weighted. The weight depends on the received SNR of different SUs, and the combined detection statistics will be calculated by:
\[ E_{MRC} = \sum_{i=1}^{N} w_{i} E_{i} , \quad (14) \]
\[ w_i = \gamma_i / \sum_{i=1}^{N} \gamma_i. \]  

(15)

In AWGN channel, the false alarm probability and detection probability of MRC scheme can be expressed as follows:

\[ P_{f_{-MRC}} = Q\left( \frac{2\gamma_{MRC}}{\sigma^2}, \sqrt{\frac{\lambda}{\sigma^2}} \right), \]  

\[ P_{f_{-MRC}} = \frac{\Gamma(u, \frac{\lambda}{2\sigma^2})}{\Gamma(u)}, \]  

(16)

(17)

where \( \gamma_{MRC} = \sum_{i=1}^{N} \gamma_i \).

(3) SLS

In SLS, FC selects the branch with the highest signal-to-noise ratio

\[ \gamma_{SC} = \max_{1 \leq i \leq N} \{ \gamma_i \}. \]  

(18)

In AWGN channel, the false alarm and detection probability of SLS scheme can be expressed as follows:

\[ P_{f_{-SC}} = Q\left( \frac{2\gamma_{SC}}{\sigma^2}, \sqrt{\frac{\lambda}{\sigma^2}} \right), \]  

\[ P_{f_{-SC}} = \frac{\Gamma(u, \frac{\lambda}{2\sigma^2})}{\Gamma(u)}, \]  

(19)

(20)

3. PERFORMANCE ANALYSIS

In this section, we evaluated the performance of the above mechanism via simulations using MATLAB. Figure 1 shows the performance comparison of the hard fusion schemes in AWGN channel. Assuming that the received signals of the cooperative cognitive nodes are independent of each other and have the same detection performance and decision threshold, the number of cooperative cognitive users is 10, SNR = 3dB, and the voting threshold in k-out-of-n criterion is set to \( K = 5 \). It can be seen that when the false alarm probability is reduced under each criterion, the detection probability will also decrease correspondingly. It can make the cognitive system use the spectrum hole of PU to the maximum extent, but it may cause great interference to PU. On the contrary, when the detection probability increases, the false alarm probability will also increase correspondingly, but it can maximize the interests of PU and make the cognitive system reduce the interference to PU as much as possible.

FIGURE 1. Performance comparison of the hard fusion schemes
Figure 2 shows the performance comparison of the above soft fusion scheme. In the experiment, the number of cooperative cognitive users is 3, SNR = -15dB, and the number of samples is 1000. From the experimental results, we can see that MRC scheme has the best detection performance, but it needs channel state information. The SLC scheme does not need any channel state information and still has better performance than SLS, that is, when the available channel information is missing, the best scheme is SLC. However, it should be noted that higher PU detection rate does not necessarily bring high throughput and energy efficiency of secondary user network.

Cooperative spectrum sensing can improve the detection accuracy, but the overhead should not be ignored. If the non-authorized users who participate in the cooperation transmit their local detection statistics or sensing results on the reporting channel, they will consume too much energy and occupy the corresponding channel bandwidth, which will cause some system overhead. Therefore, the fusion strategy for cooperative sensing based on cognitive sensor networks needs to consider the tradeoff between performance and system overhead.

4. CONCLUSIONS
Cooperative spectrum sensing technology makes full use of the spatial gain generated by sensing nodes in different geographical locations, and obtains more accurate combination decision results than single node decision. In cooperative sensing, fusion center (FC) will analyze and process the collected local detection statistics or sensing results according to a certain data fusion rule, and make the final decision on the current channel state according to the fusion results. Data fusion strategy plays an important role in perception results and system reliability. In this paper, we summarize several conventional data fusion schemes in cooperative spectrum sensing for cognitive radio networks and conduct performance analysis.

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REFERENCES
[1] Allagonda S, Chandra A, Roy S D, et al. “Detection performance of cooperative spectrum sensing with hard decision fusion in fading channels,” International Journal of Electronics, 2016, 103(2): 297-321.
[2] Farag H M, Mohamed E M. “Soft decision cooperative spectrum sensing based upon noise uncertainty estimation,” In: 2015 IEEE International Conference on Communications (ICC), London, UK, 2015, pp: 1623-1628

[3] Mukherjee A, Maheshwari A, Maiti S, et al. “Spectrum sensing for cognitive radio using quantized data fusion and Hidden Markov model,” In: 2014 International Conference on Information Systems and Computer Networks (ISCON), Mathura, 2014, pp: 133-137.

[4] Ejaz W, Hattab G, Cherif N, et al. “Cooperative spectrum sensing with heterogeneous devices: Hard combining versus soft combining,” IEEE Systems Journal, 2016, pp: 1-12.

[5] Maleki S, Chepuri S, Leus G. “Optimal hard fusion strategies for cognitive radio networks,” In: 2011 IEEE Wireless Communication Networking Conference (WCNC), Mar. 2011, pp: 1926-1931.

[6] Maleki S, Leus G, Chatzinotas S, et al. “To AND or To OR: How shall the fusion center rule in energy-constrained cognitive radio networks?,” In: 2014 IEEE International Conference on Communications (ICC), Sydney, NSW, 2014, pp: 1632-1637.

[7] Chaudhari S, Lunden J, Koivunen V, et al. “Cooperative sensing with imperfect reporting channels: Hard decisions or soft decisions?,” IEEE Transactions on Signal Processing, 2012, 60(1): 18-28.

[8] Liu Y, Yuan D, Jiang M, et al. “Analysis of square-law combining for cognitive radios over nakagami channels,” In: 5th International Conference on Wireless Communications, Networking and Mobile Computing, Beijing, 2009, pp: 1-4.

[9] Ma J, Zhao G, Li Y. “Soft combination and detection for cooperative spectrum sensing in cognitive radio networks,” IEEE Transactions on Wireless Communications, 2008, 7(11): 4502-4507.

[10] Han W, Li J, Li Z, et al. “Efficient soft decision fusion rule in cooperative spectrum sensing,” IEEE Transactions on Signal Processing, 2013, 61(8): 1931-1943.

[11] Yan Y X, Ma M D. “SNR improvement for energy detection of narrow band signal in OFDM system,” IEEE Communications Letters, 2014, 18(11): 1967-1970.