Data Fusion Schemes for Cooperative Spectrum Sensing in Cognitive Radio Networks

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Abstract— **Cooperative spectrum sensing has proven its efficiency to detect spectrum holes in cognitive radio network (CRN) by combining sensing information of multiple cognitive radio users . In this paper, we study different fusion schemes that can be implemented in fusion center. Simulation comparison between these schemes based on hard, quantized and soft fusion rules are conducted. It is shown through computer simulation that the soft combination scheme outperforms the hard one at the cost of more complexity; the quantized combination scheme provides a good tradeoff between detection performance and complexity. In the paper, we also analyze a quantized combination scheme based on a tree-bit quantization and compare its performance with some hard and soft combination schemes.**

***Index Terms*— Cooperative spectrum sensing, cognitive radio (CR), data fusion, soft, quantized and hard fusion rules.**

I. INTRODUCTION

In recent years, the demand of spectrum is rapidly increasing with the growth of wireless services. The scarcity of the spectrum resource becomes more serious. Cognitive radio provides a new way to better use the spectrum resource [1]. Therefore, a reliable spectrum sensing technique is needed. Energy detection exhibits simplicity and serves as a practical spectrum sensing scheme. As a key technique to improve the spectrum sensing for Cognitive Radio Network (CRN), cooperative sensing is proposed to combat some sensing problems such as fading, shadowing, and receiver uncertainty problems [2].

The main idea of cooperation is to improve the detection performance by taking advantage of the spatial diversity, in order to better protect a primary user, and reduce false alarm to utilize the idle spectrum more efficiently.

The three steps in the cooperative sensing process are [3]:

1- The fusion center FC selects a channel or a frequency band of interest for sensing and requests all cooperating CR users to individually perform local sensing.
2- All cooperating CR users report their sensing results via the control channel.
3- Then the FC fuses the received local sensing information to decide about the presence or absence of signal and reports back to the CR users.

As shown in Fig.1, CR3 suffers from the receiver uncertainty problem because it is located outside the transmission range of primary transmitter and it is unaware of the existence of primary receivers. So, transmission from CR3 can interfere with the reception at a primary receiver. CR2 suffers from multipath and shadowing caused by building and trees. Cooperative spectrum sensing can help to solve these problems if secondary users cooperate by sharing their information.

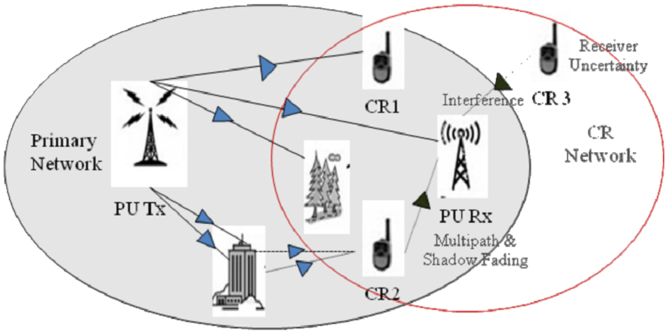

Fig. 1. Sensing problems (receiver uncertainty, multipath and shadowing).

To implement these three steps, seven elements of cooperative sensing are presented [4] as illustrated in Fig. 2.

- Cooperation models: is concerned with how CR users cooperate to perform sensing.
- Sensing techniques: this element is crucial in cooperative spectrum sensing to sense primary signals by using signal processing techniques.
- Hypothesis testing: in order to decide on the presence or absence of a primary user (PU), a statistical test is performed to get a decision on the presence of PU.
- Control channel and reporting: is used by CR users to report sensing result to the FC.
- Data fusion: is a process of combining local sensing data to make cooperation decision.
- User selection: in order to maximize the cooperative gain, this element provides us the way to optimally select the cooperating CR users.
- Knowledge base: means a prior knowledge included PU and CR user location, PU activity, and models or other information in the aim to facilitate PU detection.

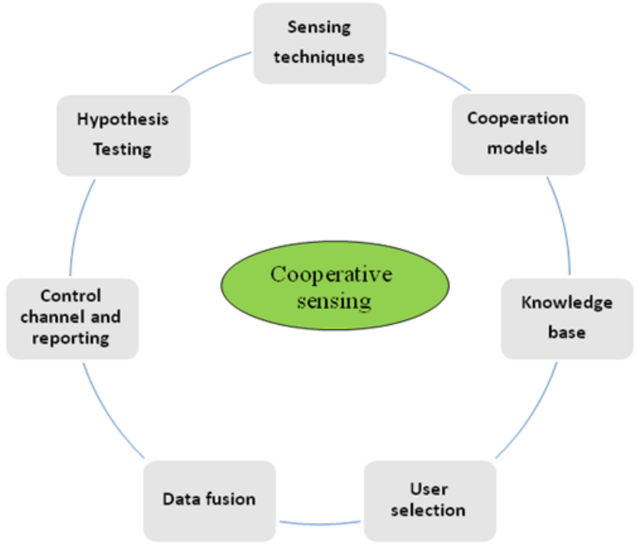

Fig. 2. Elements of cooperative spectrum sensing [4]

In this paper, we will focus on the data fusion rules. The decision on the presence of PU is achieved by combining all individual sensing information of local CR users at a central (FC) using various fusion schemes. These schemes can be classified as hard decision fusion, soft decision fusion, or quantized (softened hard) decision. The hard decision is the one in which the CR users make a one-bit decision regarding the existence of the PU, this 1-bit decision will be forwarded to the FC for fusion. In [5], a logic OR fusion rule for hard-decision combining is presented for cooperative spectrum sensing. In [6], two simple schemes of hard decision combining are studied: the OR rule and the AND rule. In [7]-[8], another sub-optimal hard decision scheme is used called Counting Rule. In [9] that half-voting rule is shown as the optimal hard decision fusion rule in cooperative sensing based on energy detection. In the case of soft decision, CR users forward the entire sensing result to the center fusion without performing any local decision. In [10] a soft decision scheme is described by taking linear combination of the measurements of the various cognitive users to decide between the two hypotheses. However, in [11] collaborative detection of TV transmissions is studied while using soft decision using the likelihood ratio test. It is shown that soft decision combining for spectrum sensing achieves more precise detection than hard decision combining. This was confirmed in [12] when performing Soft decision combination for cooperative sensing based on energy detection. Some soft combining techniques are discussed in [13-14-15] as square-law combining (SLC), equal gain combining (EGC) and square-law selection (SLS) over AWGN, Rayleigh and Nakagami-m channel.

The paper is organized as follows. We present in Section II the system model related to cooperative spectrum sensing. In Section III, we describe different fusion rules for cooperative spectrum sensing; several hard, soft and quantized schemes are proposed and discussed. Simulation results in section IV are given to compare these fusion rules. We conclude this paper in Section V.

II. SYSTEM MODEL

Consider a cognitive radio network, with K cognitive users (indexed by $k = \{1, 2. . . K\}$) to sense the spectrum in order to detect the existence of the PU. Suppose that each CR performs local spectrum sensing independently by using N samples of the received signal. The spectrum sensing problem can be formulated as a binary hypothesis testing problem with two possible hypothesis H_0 and H_1.

$$\begin{aligned} H_0 &: x_k(n) = w_k(n) \\ H_1 &: x_k(n) = h_k s(n) + w_k(n) \end{aligned} \tag{1}$$

Where $s(n)$ are samples of the transmitted signal (PU signal), $w_k(n)$ is the receiver noise for the k^th^ CR user, which is assumed to be an i.i.d. random process with zero mean and variance σ_n^2 and h_k is the complex gain of the channel between the PU and the k^th^ CR user. H_0 and H_1 represent whether the signal is absent or present respectively. Using energy detector, the k^{th} CR user will calculate the received energy as [16] :

$$E_k = \sum_{1}^{N} x_k^2(n) \tag{2}$$

In the case of soft decision, each CR user forwards the entire energy result E_k to the FC. However, for hard decision, the CR users make the one-bit decision given by $\Delta_{k,}$ by comparing the received energy E_k with a predefined threshold λ_k.

$$\Delta_k = \begin{cases} 1, E_k > \lambda_k \\ 0, \textit{otherwise} \end{cases} \tag{3}$$

Detection probability $P_{d,k}$ and false alarm probability $P_{f,k}$ of the CR user k are defined as:

$$P_{d,k} = \Pr\{\Delta_k = 1|H_1\} = \Pr\{E_k > \lambda_k|H_1\}$$
$$P_{f,k} = \Pr\{\Delta_k = 1|H_0\} = \Pr\{E_k > \lambda_k|H_0\}$$

Assuming that $\lambda_k=\lambda$ for all CR users, the detection probability, false alarm probability and miss detection $P_{m,k}$ over AWGN channels can be expressed as follows respectively [17]

$$P_{d,k} = Q_m(\sqrt{2\gamma}, \sqrt{\lambda}) \tag{4}$$

$$P_{f,k} = \frac{\Gamma(m, \lambda/2)}{\Gamma(m)} \tag{5}$$

$$P_{m,k} = 1 - P_{d,k} \tag{6}$$

where γ is the signal to noise ratio (SNR), m=TW is the time bandwidth product, $Q_N(.,.)$ is the generalized Marcum Q-function, $\Gamma(.)$ and $\Gamma(.,.)$ are complete and incomplete gamma function respectively.

III. Fusion Rules

This section describes the fusion rules that are used for the comparison.

III.1 Hard decision fusion

In this scheme, each user decides on the presence or absence of the primary user and sends a one bit decision to the data fusion center. The main advantage of this method is the easiness the fact that it needs limited bandwidth [12]. When binary decisions are reported to the common node, three rules of decision can be used, the “and”, “or”, and majority rule. Assume that the individual statistics Δ_k are quantized to one bit with Δ_k= 0, 1; is the hard decision from the k^th CR user. 1 means that the signal is present, and 0 means that the signal is absent.

The **AND** rule decides that a signal is present if ***all*** users have detected a signal. The cooperative test using the AND rule can be formulated as follows:

$$\begin{aligned} &H_1 : \sum_{k=1}^{K} \Delta_k = K \\ &H_0 : \textit{otherwise} \end{aligned} \tag{7}$$

The **OR** rule decides that a signal is present if ***any*** of the users detect a signal. Hence, the cooperative test using the OR rule can be formulated as follows:

$$\begin{aligned} &H_1 : \sum_{k=1}^{K} \Delta_k \geq 1 \\ &H_0 : \textit{otherwise} \end{aligned} \tag{8}$$

The third rule is the **voting** rule that decides on the signal presence if at least M of the K users have detected a signal with $1 \leq M \leq K$. The test is formulated as:

$$\begin{aligned} &H_1 : \sum_{k=1}^{K} \Delta_k \geq M \\ &H_0 : \textit{otherwise} \end{aligned} \tag{9}$$

A majority decision is a special case of the voting rule for M=K/2, the same as the AND and the OR rule which are also special cases of the voting rule for M=K and M=1 respectively. Cooperative detection probability Q_d and cooperative false alarm probability Q_f are defined as:

$$\begin{aligned} Q_d &= \Pr\{\Delta = 1|H_1\} = \Pr\left\{\sum_{i=1}^{K} \Delta_k \geq M \,|H_1\right\} \\ Q_f &= \Pr\{\Delta = 1|H_0\} = \Pr\left\{\sum_{i=1}^{K} \Delta_k \geq M \,|H_0\right\} \end{aligned} \tag{10}$$

Where Δ is the final decision. Note that the OR rule corresponds to the case M = 1, hence

$$Q_{d,or} = 1 - \prod_{k=1}^{K}(1 - P_{d,k}) \tag{11}$$

$$Q_{f,or} = 1 - \prod_{k=1}^{K}(1 - P_{f,k}) \tag{12}$$

The AND rule can be evaluated by setting M = K.

$$Q_{d,and} = \prod_{k=1}^{K} P_{d,k} \tag{13}$$

$$Q_{f,and} = \prod_{k=1}^{K} P_{f,k} \tag{14}$$

III.2 Soft data fusion

In soft data fusion, CR users forward the entire sensing result E_k to the center fusion without performing any local decision and the decision is made by combining these results at the fusion center by using appropriate combining rules such as square law combining (SLC), maximal ratio combining (MRC) and selection combining (SC). Soft combination provides better performance than hard combination, but it requires a larger bandwidth for the control channel [18]. It also generates more overhead than the hard combination scheme [12].

Square Law Combining (SLC): SLC is one of the simplest linear soft combining schemes. In this method the estimated energy in each node is sent to the center fusion where they will be added together. Then this summation is compared to a threshold to decide on the existence or absence of the PU and a decision statistic is given by [19]:

$$E_{slc} = \sum_{k=1}^{K} E_k \tag{15}$$

where E_k denotes the statistic from the kth CR user. The detection probability and false alarm probability are formulated as follow [19]:

$$Q_{\mathrm{d,SLC}} = Q_{mK}\left(\sqrt{2\gamma_{slc}}, \sqrt{\lambda}\right) \tag{16}$$

$$Q_{\mathrm{f,SLC}} = \frac{\Gamma(mK, \lambda/2)}{\Gamma(mK)} \tag{17}$$

Where $\gamma_{slc} = \sum_{k=1}^{K} \gamma_k$ and γ_k is the received SNR at kth CR user.

Maximum Ratio Combining (MRC): the difference between this method and the SLC is that in this method the energy received in the center fusion from each user is ponderated with a normalized weight and then added. The weight depends on the received SNR of the different CR user. The statistical test for this scheme is given by:

$$E_{mrc} = \sum_{k=1}^{K} w_k E_k \tag{18}$$

Over AWGN channels, the probabilities of false alarm and detection under the MRC diversity scheme can be given by [21]:

$$Q_{\mathrm{d,MRC}} = Q_m\left(\sqrt{2\gamma_{mrc}}, \sqrt{\lambda}\right) \tag{19}$$

$$Q_{\mathrm{f,MRC}} = \frac{\Gamma(m, \lambda/2)}{\Gamma(m)} \tag{20}$$

Where: $\gamma_{mrc} = \sum_{k=1}^{K} \gamma_k$

Selection Combining (SC): in the SC scheme, the fusion center selects the branch with highest SNR [20].

$$\gamma_{sc} = \max(\gamma_1, \gamma_2, \ldots\ldots, \gamma_K)$$

Over AWGN channels, the probabilities of false alarm and detection under the SC diversity scheme can be written as [21]:

$$Q_{\mathrm{d,SC}} = Q_m\left(\sqrt{2\gamma_{sc}}, \sqrt{\lambda}\right) \tag{21}$$

$$Q_{\mathrm{f,SC}} = \frac{\Gamma(m, \lambda/2)}{\Gamma(m)} \tag{22}$$

III.3 Quantized data fusion

In this scheme, we try to realize a tradeoff between the overhead and the detection performance. Instead of one bit hard combining, where there is only one threshold dividing the whole range of the detected energy into two regions, a better detection performance can be obtained if we increase the number of threshold to get more regions of observed energy.

In [12], a two-bit hard combining scheme is proposed in order to divide the whole range of the detected energy into four regions. The presence of the signal of interest is decided at the FC by using the following equation:

$$\sum_{i=0}^{3} w_i n_i \geq L \tag{23}$$

where L is the threshold and it is equal to the weight of the upper region, n_i is the number of observed energies falling in region i and w_i is the weight value of region i with w_0=0 w_1= 1, w_2= 2 and w_3= 4.

In this paper, we extend the scheme of [12] to a three-bit combining scheme. In the three-bit scheme, seven threshold λ_1, λ_2… and λ_7, divide the whole range of the statistic into 8 regions, as depicted in Fig. 3. Each CR user forwards 3 bit of information to point out the region of the observed energy. Nodes that observe higher energies in upper regions will forward a higher value than nodes observing lower energies in lower regions.

The three-bits combining scheme is performed in four steps:

1: Define a quantization threshold λ_i (i=1 . . . 7) for each region according to the maximal received energy of the signal.

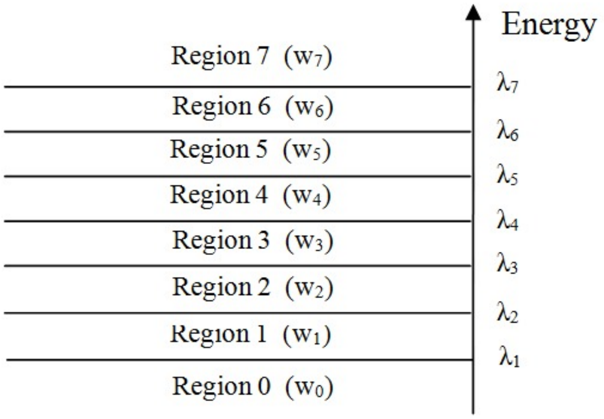

Fig. 3. Principle of three-bit hard combination scheme

2: Each user makes a local decision by comparing the received energy with the thresholds predefined in 1, and sends 3-bits information to the FC.

3: The FC sums the local decisions ponderated with weights w_i (i=0.., 7). In our case, we have taken: $w_0=0$, $w_1=1$, $w_2=2$, $w_3=3$, $w_4=4$, $w_5=5$, $w_6=6$, $w_7=7$.

4: The final decision is made by comparing this sum with a threshold L.

$$\sum_{k=1}^{K} w_{i,k} \geq L \tag{24}$$

IV. Simulations and results

In this section we study the detection performance of our scheme through simulations, and compare its performances with soft and hard fusion schemes. First, we present the performance of the hard combining schemes as depicted in Fig. 4. Secondly, we will compare the performance of the different fusion rules in case of soft combining. Next, the two-bit and the three-bit quantized schemes are compared in term of detection performance.

For the hard decision, we present in Fig. 4 the ROC curves of the ‘AND’ and the ‘OR’ rule, and compare it to the detection performance of a single CR user. For the simulations, we consider 3 CR users. Each user has a SNR of -2db. As shown in Fig. 4, the OR rule has better detection performance than the AND rule, which provides slightly better performance at low Pfa than the OR, because the data fusion center decide in favor of H1 when at least one CR user detects the PU signal. However in the AND rule, to decide of the presence of a primary user, all CR users must detect the PU signal.

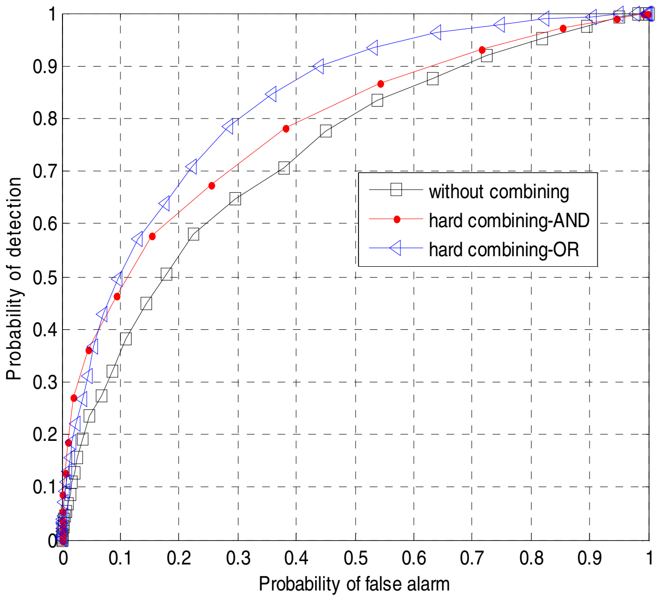

Fig. 4. ROC for the hard fusion rules under AWGN channel, SNR= -2dB, K=3 users, and energy detection over 1000 samples.

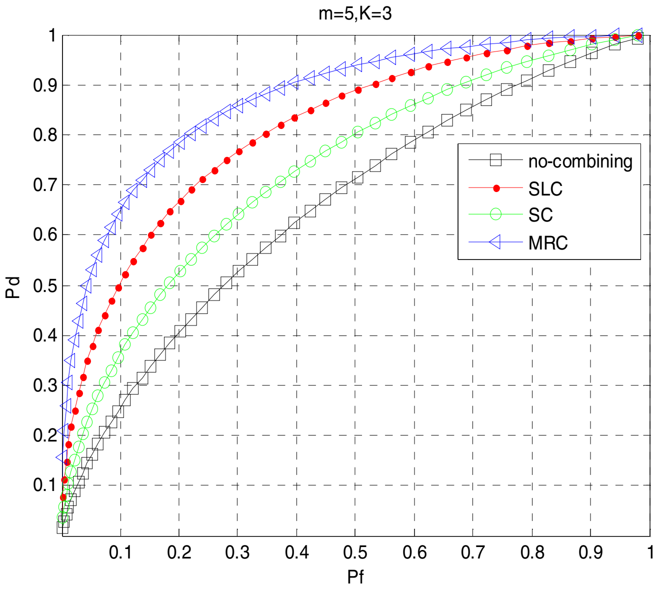

Fig. 5. ROC for soft fusion rules under AWGN channel with K=3 users, and energy detection with m=5.

Fig. 5 shows the ROC curves of different soft combination schemes discussed in section III.2 under AWGN channel. For the simulations, each CR user sees a different SNR. We observe from this figure that the MRC scheme exhibits the best detection performance, but it requires channel state information. The SLC scheme does not require any channel state information and still present better performance than SC. When no channel information is available, the best scheme is SLC.

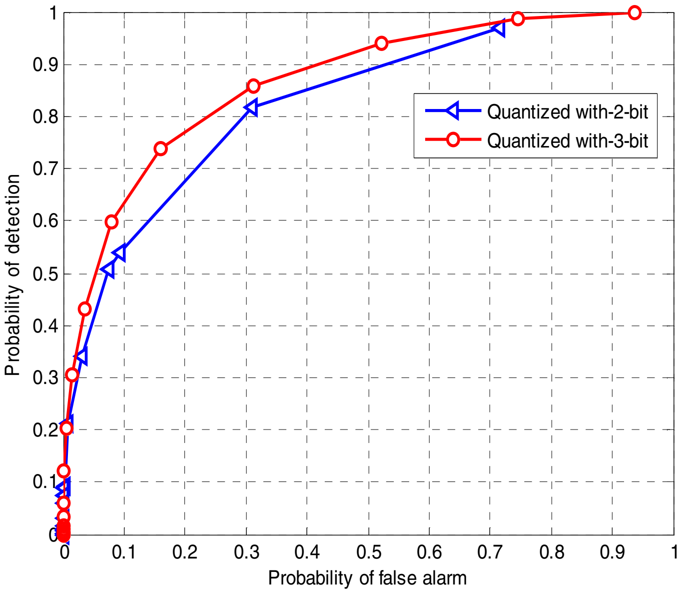

Fig. 6. ROC curves for quantized data fusion under AWGN channel with SNR=-2db, K=4users and N=1000 samples

Fig. 6 shows the ROC curves for quantized data fusion with 2-bit and 3-bit quantized combination, the figure indicates that the proposed 3-bit combination scheme shows much better performance than the 2-bit combination scheme at the cost of one more bit of overhead for each CR user, this scheme can achieve a good tradeoff between detection performance and overhead.

For comparison, we show in Fig. 7 the ROC curves for the different fusion rules under AWGN channel. As the figure indicates, all fusions method outperform the single node sensing, the soft combining scheme based on SLC rule outperforms the hard and quantized combination at the cost of control channel overhead, the 3-bit quantized combination scheme shows a comparable detection performance with the SLC, with less overhead.

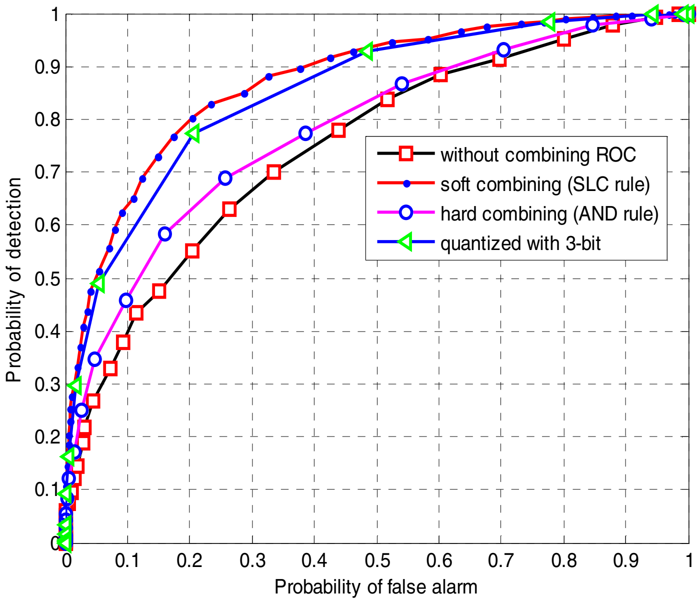

Fig. 7. ROC for combining fusion rules under AWGN channel with K=3 users, SNR=-2db and energy detection with N=1000 samples.

V.CONCLUSION

In this paper, the effect of fusion rules for cooperative spectrum sensing is investigated. It is shown that the soft fusion rules outperform the hard fusion rules. However, these benefits are obtained at the cost of a larger bandwidth for the control channel. The hard fusion rules occur with less complexity, but also with a lower detection performance than soft combination schemes. The proposed quantized three-bit combination scheme wins advantage of the soft and the hard decisions schemes with a tradeoff between overhead and detection performance. In practical application, we can select an appropriate method of data fusion and decision algorithms according to the requirement of detection performance and the requirement of the available bandwidth for the reporting channel.

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