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A novel multistage decision fusion for cognitive sensor networks using AND and OR rules

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ABSTRACT

We propose a centralized radix-2 multistage decision fusion strategy comprising simple AND and OR rules for cooperative spectrum sensing in cognitive sensor networks. Earlier works on centralized decision fusion show the half-voting and majority rules to be optimum in many spectrum sensing scenarios in terms of minimizing the decision error (or equivalently maximizing the probability of correct decision). We consider a commonly occurring case in spectrum sensing in which the detection probability of a cognitive radio enabled sensor node is greater than its false-alarm probability. For this case, we consider five scenarios and demonstrate that the proposed method either performs better than half-voting and majority rules or exhibits a comparable performance. In this context, we also establish a criterion to make a choice between the AND and OR rules and compute the optimum number of nodes participating in cooperative spectrum sensing for these rules to maximize the correct decision probability.

1. Introduction

A wireless sensor network (WSN) comprises many sensors willing to communicate with one another or with a base station for manifold applications [1,2]. Such sensors are equipped with sensing, processing and short-range communication capabilities [3,4] and usually use license-free Industrial, Scientific and Medical (ISM) band for communication [4,5]. However, this band is getting overcrowded with many applications using it, so WSNs with the capability to sense and use the licensed spectrum, when it is available, are desired [5,6]. These spectrum sensing and decision making capabilities make the network a cognitive radio wireless sensor network (CRWSN or CSN) [7–9]. There are various methods by which a cognitive radio enabled sensor node (CR node) can identify spectrum occupancy [10,11]. The detection performance of a sensing technique is judged in terms of its detection and false-alarm probabilities (abbreviated as DP and FAP respectively). Standards, such as IEEE802.22, prescribe a lower limit on the DP and an upper limit on the FAP to guarantee a minimum detection performance [12]. It is, however, still desirable to further increase the DP and decrease the FAP. A higher DP is desired from the standpoint of a licensed user (also called primary user or PU), and a lower FAP is desired from the standpoint of a cognitive user (also called secondary user or SU) [13]. A higher DP ensures less interference to the PU from the SU, and a lower FAP ensures more spectrum opportunity for the SU. For a CSN, being an SU, it is important to maximize the utilization of unused spectrum. At the same time, it is equally important to minimize the interference with the PU. This can be ensured by maximizing the correct decision probability, which we define as the probability with which the FC decides the spectrum to be occupied or available when it is actually occupied or available respectively. We, therefore, consider the maximization of the correct decision probability in this work.

In order to improve the detection performance, multiple CR nodes are made to cooperate in decision making [14,15]. This cooperative spectrum sensing (CSS) may be distributed or centralized. In the centralized scheme, a fusion center (FC) collects the information from the CR nodes and takes a final decision about the spectrum availability. If the information sent by the CR nodes are their 1-bit decisions, it is called decision fusion (DF), otherwise it is known as data fusion [16]. We follow the DF schemes for their spectral and energy efficiency, and comparable performance with the data fusion in many practical scenarios [14].

Earlier works on DF consider a variety of counting rules such as OR, AND, half-voting (HV), majority and the general K-out-of-N rules [13,17–23]. Zhang et al. [18] conclude that the optimal counting rule that minimizes the total error rate, which is equivalent to maximizing the correct decision probability, is the HV rule. Maleki et al. [19,20] show that the majority rule is optimal or near optimal in maximizing the throughput. Wang et al. [21] show that

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the majority rule is optimal when the FAP is smaller than 0.5. Axell et al. [22] maintain that when the FAP and the miss-detection probability (MDP, which is the complement of DP) of the individual CR nodes are of the same order, the majority rule is optimal. In case the FAP is much smaller than the MDP, the optimal voting rule shifts toward the OR rule. In the other extreme case it shifts toward the AND rule. Since the FAP and MDP are usually of the same order [18], the optimal voting rule is K near to the middle values $(N/2)$ in the K-out-of-N rule. Chaudhari et al. [23] concur with this notion in the context of erroneous reporting channel. These counting rules are essentially single-stage DF schemes for two reasons — one, the CR nodes transmit their decisions directly to the FC; two, the FC combines these 1-bit decisions at once to make a final decision.

Here, we propose a centralized radix-2 multistage DF scheme comprising AND and OR rules. We use the term 'radix-2' from the celebrated Fast Fourier Transform (FFT) algorithms [24]. We show that the proposed strategy has a potential to give higher correct decision probability compared to the HV and the majority rules. We consider five scenarios to demonstrate the results.

Related work Some multistage fusion schemes, in the general event detection context, are available in the literature [17,25–29]. Varshney [17], Vishwanathan and Varshney [25], and Vishwanathan and Ahsant [26] describe multistage fusion strategies based on tandem and tree topologies in which a node fuses the decision(s) of node(s) one level down with its own observations and transmits its decision to another node one level up in the hierarchy. The process continues until a FC makes a final decision. Gubner et al. [27], and Zhang et al. ([28,29] and references mentioned therein) discuss a balanced binary relay tree structure for DF, in which sensors making the observations are the leaf nodes. Pair of leaf nodes transmit their decisions to a fusion node one level up in the hierarchy. Every fusion node combines two such decisions and makes its own decision following the AND or the OR rule and transmit it to the next higher level. The fusion nodes here act as relays for they themselves do not make any observations; they just combine the decisions of the previous level and transmit the new decisions to the next level. At the top level a FC combines the two decisions of the penultimate level to make a final decision.

Our scheme is similar to this latter scheme; however, we assume a scenario where it is practicable for the CR nodes to transmit their decisions to the FC directly. The multistage scheme is, therefore, implemented within the FC. Zhang et al. [28,29], in their first paper [28], focus on obtaining the probability error bounds as the number of sensors (leaf nodes) and hence the height of the tree grows. In their second paper [29], they discuss the optimality of error probability using AND and OR rules. We, on the other hand, focus on comparing the performance of our scheme in terms of the correct decision probability, and the computational complexity in determining the global DP and FAP, with the conventional counting rules. In addition, we give a condition for making a choice between the AND and the OR rules, and show that a 'binary' structure yields maximum correct decision probability in many situations when these rules are used.

Contributions We assume a CSN with identical DP and FAP pair across all CR nodes, which is a reasonable assumption for a network spread over a small geographical area [16,30,7]. We further assume that the DP is greater than the FAP, which is true for any sensible detection system [31]. We consider the maximization of correct decision probability using a multistage DF mechanism and do the following:

- Establish a criterion to make a choice between the AND and the OR rules.
- Compute the optimum number of CR nodes to maximize the correct decision probability for AND and OR rules and show this number to be 'two' for a common scenario in which the sum of DP and FAP of a CR node is approximately 'one' [18]. It shows that a 'binary' structure of DF is the best in such scenarios.
- Using these results, develop a radix-2 multistage DF strategy with a view to maximize the correct decision probability by maximizing the difference of cooperative DP and cooperative FAP.
- Show through simulations that the radix-2 multistage DF always outperforms the AND and the OR rules, and it also either performs better than the HV and the majority rules or exhibits a comparable performance.
- Show that the computational complexity of the proposed scheme is much lower (of the order of $\log_2 N$) compared to that of the HV and majority rules (of the order of N^2) in determining the global DP and FAP at the FC.

The rest of the paper is organized as follows: In Section 2, we introduce the correct decision probability and in Section 3, we discuss its maximization for AND and OR rules. In Section 4, we present the radix-2 multistage DF strategy and discuss the rationale behind its effectiveness. In Section 5, we give the simulation results and discussions. In Section 6, we conclude the paper giving future research directions.

2. System model

In spectrum sensing literature, the phrases 'PU present', 'PU active', or 'spectrum occupied' are used interchangeably. Similarly, it applies for the phrases 'PU absent', 'PU inactive', or 'spectrum available'. We follow the same convention. Let the two hypotheses that represent the actual presence or absence of the PU be denoted by H_1 and H_0 respectively, and that decided by the FC by $\mathcal{H}_1$ and $\mathcal{H}_0$ respectively. The cooperative DP and FAP are respectively defined as $Q_d \triangleq \Pr[\mathcal{H}_1|H_1]$ and $Q_f \triangleq \Pr[\mathcal{H}_1|H_0]$. The FC takes a correct decision if it decides in favor of PU being active when it is actually active, or if it decides in favor of PU being inactive when it is actually inactive. If α and β denote the probabilities of PU being active and inactive respectively, the probability of taking the correct decision by the FC can be defined as:

$$\Pr[C] \triangleq \alpha Q_d + \beta(1 - Q_f) \tag{1}$$

Conventionally, a FC fuses 1-bit decisions (1 or 0 respectively for the presence or absence of PU) of individual CR nodes at once and declares $\mathcal{H}_1$ or $\mathcal{H}_0$ as per the K-out-of-N rule. If D_i denotes the decision of ith CR node, the K-out-of-N rule for an N node system is given as follows [18]:

$$\sum_{i=1}^{N} D_i \underset{\mathcal{H}_0}{\overset{\mathcal{H}_1}{\gtrless}} K \tag{2}$$

Eq. (2) becomes OR rule for $K = 1$, AND rule for $K = N$, half-voting (HV) rule for $K = \lceil N/2 \rceil$ and majority rule for $K > \lceil N/2 \rceil$. The cooperative DP and FAP for AND, OR and the K-out-of-N rules are respectively given as:

$$Q_{z,\mathrm{AND}} = \prod_{i=1}^{N} P_{zi} \tag{3}$$

$$Q_{z,\mathrm{OR}} = 1 - \prod_{i=1}^{N} (1 - P_{zi}) \tag{4}$$