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The decision fusion in the wireless network with possible transmission errors

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ABSTRACT

In a wireless sensor network, a fusion center may receive incorrect information from local sensors, with some probabilities of transmission errors, due to channel fading. To cope with such a problem, we generalize the likelihood-ratio-test method of Chen and Willett (2005) [7] and derive optimal local sensor compression rules that minimize the Bayesian cost under a given fusion rule and transmission error probabilities. Our proposed method is able to operate without conditional independence between sensor data, which is often required by existing methods. Numerical examples are also used to validate the performance through receiver operating characteristics curves. These examples highlight the interesting features of our method compared to those in ideal situations.

1. Introduction

A wireless sensor network (WSN) is prone to channel fading and transmission error problems. In fact, over the past decade, numerous methods have been developed that target transmission errors and achieve fault-tolerant decisions. Research works in [1–21] discuss these problems in detail. For examples, the impact of channel errors on decentralized decision performance in a WSN was examined by Chamberland and Veeravalli [4]. Their results show that, although the fading channels are detrimental to the performance of a WSN, the quality of sensor observations has a greater impact on the overall performance. Chen and Willett [7], Chen et al. [8] and Niu et al. [16], among others, solved the parallel decision fusion problem under fading channels with conditional independence between sensor observations. Given a fusion rule, they obtained optimal sensor compression rules via a likelihood-ratio-test (LRT) method. Furthermore, they derived three sub-optimal fusion rules – namely, the two-stage fusion statistic based on Chair–Varshney fusion, the maximal ratio combiner fusion statistic, and the equal gain combiner fusion statistic – and compared their performances.

In this paper, we tackle the decentralized decision fusion problem in the presence of channel transmission errors and related sensor data. To this end, we generalize Chen's LRT method in [7] to also cater to correlated sensor data. Here we consider a fault-tolerant model by introducing the transmission error probabilities into the decentralized decision fusion model in [22]. In a way analogous to that done for the ideal channel situation in [22], we obtain a necessary condition for optimal sensor compression rules, such that one can also use them to design the iterative algorithm for each sensor rule. In the presence of dependencies between sensor observations, the optimal sensor rules in [7], using the likelihood-ratio-test, are proved

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to be special cases of our proposed method. Moreover, our method can work for fading channel situations but is no more computationally demanding than those for non-fading channels in [22]. At the end of this paper, we provide some numerical examples to compare the performances of our method with those of existing works in terms of the receiver operating characteristics (ROC) curves. The ROC curves based on our method show some interesting features that are different from those obtained in ideal channel situation.

This paper is organized as follows. We first formulate the problem in Section 2. In Section 3, we establish the necessary condition for the optimal sensor compression rules and its associated iterative algorithm. In Section 4, we prove that the sensor rules based on LRT method are special cases within our method. Section 5 provides some numerical examples. The conclusion and discussions are drawn in Section 6.

2. Problem formulation

We consider a wireless parallel sensor network in which a fusion center decides the presence or absence of a phenomenon of interest based on l local sensors' transmissions. Let H_0 and H_1 denote absence and presence, respectively. Each sensor compresses its observation into a bit (0 stands for H_0 and 1 for H_1) and sends it through a channel to the fusion center, where the received bits are used to yield a final decision according to the given fusion rule.

Let y_i, $i = 1,2,\ldots,l$, denote the observation of the ith sensor, and let $I_i = I_i(y_i)$, $i = 1,2,\ldots,l$, denote its corresponding binary bit. The two joint conditional probability density functions (PDFs) $p(y_1,y_2,\ldots,y_l|H_0)$ and $p(y_1,y_2,\ldots,y_l|H_1)$ are assumed to be known.

The fading channels are assumed to have the following properties:

Property 1. *The channels connecting the sensors to the fusion center are not totally reliable, so the fusion center may receive incorrect bit due to possible transmission error. Let $I_i^0, i = 1, 2, \ldots, l$, denote the bits received by the fusion center. The two error probabilities of the channel between the ith sensor and the fusion center are:*

$$P_i^{c1} = P\left(I_i^0 = 0|I_i = 1\right) \text{ and} \tag{2.1}$$

$$P_i^{c0} = P\left(I_i^0 = 1|I_i = 0\right), \tag{2.2}$$

where P_i^{c1} describes the error probability that the ith sensor sends 1 while the fusion center receives 0, and P_i^{c0} describes the alternative case. The channel is assumed to maintain stable transmissions such that its two error probabilities are invariant.

Property 2. *The link error is statistically independent of the sensor compression, hence, the probabilities of receiving I_i^0 under H_j, $j = 0, 1$, are:*

$$\begin{aligned} P\left(I_i^0 = 0|H_j\right) &= P(I_i = 0|H_j)\left(1 - P_i^{c0}\right) + P(I_i = 1|H_j)P_i^{c1}, \\ P\left(I_i^0 = 1|H_j\right) &= P(I_i = 1|H_j)\left(1 - P_i^{c1}\right) + P(I_i = 0|H_j)P_i^{c0}. \end{aligned} \tag{2.3}$$

Property 3. *The l transmissions are independent across the channels; i.e.:*

$$P\left(I_1^0, I_2^0, \ldots, I_l^0|I_1, I_2, \ldots, I_l\right) = \prod_{k=1}^{l} P\left(I_k^0|I_k\right). \tag{2.4}$$

Here we first consider the case of independent channel transmissions. In a later section, we will study the case that channel transmissions are correlated either within the same channel or across different channels, in a way similar to that in the independent channel transmissions.

The fusion center yields the final decision based on the received binary bits $\left(I_1^0, I_2^0, \ldots, I_l^0\right)$; i.e.:

$$U_0 = F\left(I_1^0, I_2^0, \ldots, I_l^0\right),$$

where F is a given fusion rule. The fusion rule F divides the collection of all 2^l possible values of $\left(I_1^0, I_2^0, \ldots, I_l^0\right)$ into the two following parts, which are related to H_0 and H_1, respectively:

$$\begin{aligned} \mathcal{H}_0 &= \left\{\left(I_1^0, I_2^0, \ldots, I_l^0\right)|F\left(I_1^0, I_2^0, \ldots, I_l^0\right) = 0\right\}, \\ \mathcal{H}_1 &= \left\{\left(I_1^0, I_2^0, \ldots, I_l^0\right)|F\left(I_1^0, I_2^0, \ldots, I_l^0\right) = 1\right\}. \end{aligned} \tag{2.5}$$

Because the joint conditional PDFs $p(y_1,y_2,\ldots,y_l|H_0)$ and $p(y_1,y_2,\ldots,y_l|H_1)$ are already known, the problem is reduced to searching for optimal local sensor compression rules that minimize the cost under the given fusion rule. If the channels are error-free, i.e., the bit received by the fusion center always equals that sent from the corresponding sensor, the optimal sensor rules with dependent sensor observations are as established in [2,23,24] and the monograph [22]. In the following sections, the decision fusion method with transmission errors and correlated sensor observations will be discussed.