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Centralized and decentralized detection with cost-constrained measurements ☆

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ABSTRACT

Optimal detection performance of centralized and decentralized detection systems is investigated in the presence of cost constrained measurements. For the evaluation of detection performance, Bayesian, Neyman–Pearson and *J*-divergence criteria are considered. The main goal for the Bayesian criterion is to minimize the probability of error (more generally, the Bayes risk) under a constraint on the total cost of the measurement devices. In the Neyman–Pearson framework, the probability of detection is to be maximized under a given cost constraint. In the distance based criterion, the *J*-divergence between the distributions of the decision statistics under different hypotheses is maximized subject to a total cost constraint. The probability of error expressions are obtained for both centralized and decentralized detection systems, and the optimization problems are proposed for the Bayesian criterion. The probability of detection and probability of false alarm expressions are obtained for the Neyman–Pearson strategy and the optimization problems are presented. In addition, *J*-divergences for both centralized and decentralized detection systems are calculated and the corresponding optimization problems are formulated. The solutions of these problems indicate how to allocate the cost budget among the measurement devices in order to achieve the optimum performance. Numerical examples are presented to discuss the results.

1. Introduction

In this paper, centralized and decentralized hypothesis-testing (detection) problems are investigated in the presence of cost constrained measurements. In such systems, decisions are performed based on measurements gathered by multiple sensors, the qualities of which are determined according to assigned cost values. The aim is to develop optimal cost allocation strategies for the Bayesian, Neyman–Pearson, and *J*-divergence criteria under a total cost constraint. In the case of centralized detection, a set of geographically separated sensors sends all of their measurements to a fusion center, and the fusion center decides on one of the hypotheses [1]. On the other hand, in decentralized detection, sensors transmit a summary of their measurements to the fusion center [2]. For quantifying the costs of measurement devices (sensors), the model in [3] is employed in this study. According to [3], the cost of a measurement device is basically determined by the number of amplitude levels that it can reliably distinguish. This cost model can be used in sensor network applications in which measurements are performed via various sensors. As an example, for fire detection in a forest, there can exist a finite number of sensors performing temperature measurements, and according to these measurements, the decision on the presence of fire is made. The accuracy of the decision depends on the quality of the measurements collected by the sensors. If the cost allocated to a sensor is higher, the measurement becomes less noisy as modeled in [3]. Similar applications can be considered in wireless cognitive radio, sonar and radar systems.

Detection and estimation problems considering system resource constraints have extensively been studied in the literature [4–22]. In [4], measurement cost minimization is performed under various estimation accuracy constraints. In [5], optimal distributed detection strategies are studied for wireless sensor networks by considering network resource constraints, where it is assumed that observations at the sensors are spatially and temporally independent and identically distributed (i.i.d.). Two types of constraints are taken into consideration related to the transmission power and the communication channel. For the communication channel, there exist two options, which are multiple access and

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parallel access channels. It is shown that using a multiple access channel with analog communication of local likelihood ratios (soft decisions) is asymptotically optimal when each sensor communicates with a constant power [5]. In [6], binary decentralized detection problem is investigated under the constraint of wireless channel capacity. It is proved that having a set of identical sensor is asymptotically optimal when the observations conditioned on the hypothesis are i.i.d. and the number of observations per sensor goes to infinity. In [7], a decentralized detection problem is studied, where the sensors have side information that affects the statistics of their measurements and the network has a cost constraint. The author examines wireless sensor networks with a cost constraint and a capacity constraint separately. In both scenarios, the error exponent is minimized under the specified constraints. The study in [7] produces a similar result to that in [6] for the scenario with the capacity constraint. In addition, [7,8] have the same results for scenario with the power constraint. It is obtained that having identical sensors which use the same transmission scheme is asymptotically optimal when the observations are conditionally independent given the state of the nature.

In [9], the decentralized detection problem is studied in the presence of system level costs. These costs stem from processing the received signal and transmitting the local outputs to the fusion center. It is shown that the optimum detection performance can be obtained by performing randomization over the measurements and over the choice of the transmission time. In [10], the aim is to minimize the probability of error under communication rate constraints, where the sensors can censor their observations. The optimum result is obtained by censoring uninformative observations and sending informative observations to the fusion center. In [11], the aim is to obtain a network configuration that satisfies the optimum detection performance under a given cost constraint. The cost constraint depends on the number of sensors employed in the network. In [12], the optimal power allocation for distributed detection is studied, where both individual and joint constraints on the power that sensors use while transmitting their decisions to the fusion center are taken into consideration. The optimal detection performance is obtained for the proposed power allocation scheme. In [13], a binary hypothesis testing problem is investigated under communication constraints. The proposed algorithm determines a data reduction rate for transmitting a reduced version of data and finds the performance of the best test based on the reduced data. In [14], the decentralized detection problem is investigated under both power and bandwidth constraints. It is shown that combining many ‘not so good’ local decisions is better than combining a few very good local decisions in the case of large sensor systems. In [15–17], the decentralized detection problem is studied with fusion of Gaussian signals. It is stated that there is an optimal number of local sensors that achieves the highest performance under a given global power constraint, and increasing the number of sensors beyond the optimal number degrades the performance. In [18], the authors investigate decentralized detection and fusion performance of a sensor network under a total power constraint. It is shown that using non-orthogonal communication between local sensors and the fusion center improves fusion performance monotonically. In [19], the optimization of detection performance of a sensor network is studied under communication constraints, and it is found that the optimal fusion rule is similar to the majority-voting rule for binary decentralized detection. In [21], the sensor (or, sample) selection problem is studied for distributed detection. The authors seek the best subset of data samples that results in a desired detection probability. To this aim, the number of selected sensors that perform the sensing task is minimized under a given probability of error constraint for the Bayesian criterion and under false-alarm and miss-detection rate constraints for the Neyman–Pearson criterion. In addition, a dual problem is also proposed such that the probability of error is minimized for a constant number of selected sensors in the Bayesian criterion. For the Neyman–Pearson criterion, it is aimed to minimize the probability of miss detection under a given false alarm constraint and a fixed number of selected sensors. It is found that for conditionally independent observations, the best sensors are the ones with the largest local average log-likelihood ratio and the smallest local average root-likelihood ratio in the Neyman–Pearson and Bayesian setting, respectively. As in [21], the sensor selection problem is studied in [22], where the aim is to find a subset of p out of n sensors that yield the best detection performance. The authors show numerically the validity of the Chernoff and Kullback–Leibler sensor selection criteria by illustrating that they lead to sensor selection strategies that are nearly optimal both in the Bayesan and Neyman–Pearson sense.

Based on the cost function proposed in [3] for obtaining measurements, various studies have been performed on estimation with cost constraints [4,20]. In particular, Ref. [4] considers the costs of measurements and aims to minimize the total cost under various estimation accuracy constraints. In [20], average Fisher information maximization is studied under cost constrained measurements. On the other hand, Ref. [23] investigates the tradeoff between reducing the measurement cost and keeping the estimation accuracy within acceptable levels in continuous time linear filtering problems. In [24], the channel switching problem is studied, where the aim is to minimize the probability of error between a transmitter and a receiver that are connected via multiple channels and only one channel can be used at a given time. In that study, a logarithmic cost function similar to that in [3] is employed for specifying the cost of using a certain channel.

Although costs of measurements have been considered in various estimation and channel switching problems such as [4,20,23,24], there exist no studies in the literature that consider the optimization of both centralized and decentralized detection systems in the presence of cost constrained measurements based on a specific cost function as in [3]. In this study, we first consider the centralized detection problem and propose a general formulation for allocating the cost budget to measurement devices in order to achieve the optimum performance according to the Bayesian criterion. Also, a closed-form expression is obtained for binary hypothesis testing with Gaussian observations and generic prior probabilities. In addition, it is shown that the probability of error expression for the Gaussian case is convex with respect to the total cost constraint in the case of equally likely binary hypotheses (Lemma 1). Then, we investigate the decentralized detection problem in the Bayesian framework with some common fusion rules, and present a generic formulation that aims to minimize the probability of error by optimally allocating the cost budget to measurement devices. A numerical solution is proposed for binary hypothesis testing with Gaussian observations. As convexity is an important property for the optimization problems, the convexity property is explored for the case of two measurement devices (Lemma 2). Furthermore, the Neyman–Pearson and J-divergence criteria are investigated for the cost allocation problem in order to achieve the optimum detection performance. The general optimization problems are proposed for both criteria and the Gaussian scenario is investigated as a special case. As for the Bayesian criterion, both centralized and decentralized detection systems are taken into consideration.

The remainder of the paper is organized as follows: In Section 2, the optimal cost allocation among measurement devices is studied for the Bayesian criterion. In Section 3, the problem is investigated in the Neyman–Pearson framework. In Section 4, the optimization problems obtained according to J-divergence are examined. In Section 5, numerical examples that illustrate the obtained results are presented. Finally, conclusions are presented in Section 6.