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Robust decentralized estimation fusion in energy-constrained wireless sensor networks with correlated noises

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ABSTRACT

Decentralized estimation fusion based on quantized local estimates is investigated. Motivated by the fact that the variance of quantization noise suffers from bounded uncertainty, we address the robust quantized estimation fusion problem in energy constrained wireless sensor networks. The quantization levels and fusion weights are jointly determined by minimizing worst-case of mean squared error of fused estimate among the uncertainties. Moreover, the effects of observation noise correlations on the fusion performance is explored by considering three different correlation scenarios. The optimal solution of the proposed robust fusion problem in each scenario is derived, in a closed-form or by solving a semidefinite programming. Theoretical analysis indicates that if the correlations exist, the fusion performance might improve or degrade, depending on correlation structure. However, appropriate usage of the correlations in fusion center can asymptotically improve the estimation fusion performance. Numerical simulations are provided to verify the theoretical analysis, and the results illustrate the good performance of the proposed method.

1. Introduction

Wireless Sensor Networks (WSNs) are the integration of sensor technology, embedded computer technology, communication technology and distributed information process technology, which can be widely applied in environmental monitoring, industrial monitoring, target tracking, battlefield surveillance and agriculture [1], etc. Given the great technological advances and the enormous potential for applicability, research in decentralized data fusion in the WSNs is receiving more and more attentions [2,3].

A widely used architecture of decentralized data fusion in the WSNs consists of a fusion center (FC) and a number of geographically distributed sensors, where each sensor collects its local observations and transmits its local estimate to the FC via a wireless link. The classical best linear unbiased estimator (BLUE) [4] linearly combines the real-valued local estimates to minimize the mean squared error (MSE). However, an important characteristic of a WSN is its energy efficiency. Subject to severe energy and bandwidth limitations [5,6], it is unrealistic for sensors to transmit their real-valued local estimates to FC. A more practical decentralized estimation scheme is to let only a quantized version of local estimate transmit to FC, and then the FC combines all the received discrete messages to reach a final estimate [5].

During the last two decades, plenty of energy/power-efficient decentralized estimation methods based on the quantized local estimates have been proposed in the literature (see, e.g., [7–12]). The decentralized estimation strategy in an inhomogeneous sensing environment in [8] lets the quantization level be proportional to the logarithm of local signal-to-noise ratio (SNR). A power scheduling scheme developed in [9] optimizes the quantization levels by minimizing the L^2-norm of the sensor energy vector under a given MSE performance constraint. The method proposed in [10] is to determine the optimal quantization levels with a given total energy budget. Instead of requiring the knowledge of local noise variances, the approach in [11] relies on a statistical model of sensor noise variances. A corresponding energy constrained decentralized estimation scheme via partial sensor noise variance knowledge is proposed in [12].

Among the aforementioned methods, the most popular quantization scheme is the probabilistic quantization method [8–10] due to its attractive statistical properties. However, one drawback of the probabilistic quantization strategy is that the variance of the quantization noise suffers from bounded uncertainty. To the best of our knowledge, there is no existing method dealing with such uncertainties in the literature. To remedy this drawback, we address

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the robust decentralized estimation fusion problem for energy-constrained WSNs in this paper.

In practice, due to the inexactness of mathematical model and variety of the WSN's environment, the phenomena of uncertainties in decentralized estimation fusion are unavoidable. The robust estimation fusion problem has been extensively studied (see, e.g., [13–16]), where the minimax strategy is most commonly employed. Therefore, we explore a minimax robust decentralized estimation fusion scheme to deal with the uncertainties in the quantized noise covariance, which aims to find both the optimal quantization levels and a linear estimation fusion that minimize the worst-case MSE of the fused estimate among the uncertainties under an energy constraint.

On the other hand, the sensor observation noises can be correlated in practical applications in general. It is particularly common in the WSNs, as for example some sensor nodes are likely to be exposed to the same external noise biasing their observations, especially when the sensors are densely deployed [17,18]. As pointed out in [2], such correlation is particularly important in multi-sensor data fusion. Some early work in this area has already incorporated the noise correlations into the decentralized estimation formulations [3,19,20,17,18]. The decentralized estimator in [3] involves the correlated observation noises in estimating a parameter vector. In [19], the quantization levels are determined by using the knowledge of covariance matrix and the final decentralized estimate is obtained via a quasi-BLUE linear fusion rule. The power saving can be achieved by considering the noise covariance matrix in the design in [20]. In [17,18], the decentralized estimators under an analog communication framework in different correlation scenarios are developed. Recently, the problem of sensor selection with correlated measurement noises is investigated in [21]. The benefits of noise correlations have also been studied in a number of electrical engineering applications including neural signal processing, statistical signal processing and information theory, as exemplified in [22] and references therein.

Motivated and inspired by the aforementioned works, we further investigate the effects of correlations among observation noises on the MSE of the proposed robust decentralized estimation. The natural question will be whether or not it is possible to exploit the noise correlations to improve the robust estimation fusion performance. In order to answer this question, we focus on the following three scenarios: (i) Sensors have uncorrelated observation noises and the FC is aware of those; (ii) Sensors have correlated observation noises and the FC has no knowledge of cross-correlations; (iii) Sensors have correlated observation noises and the FC has full knowledge of cross-correlations.

Our contributions of this paper are highlighted as follows:

First, in contrast to the existing quasi-BLUE estimation fusion method, we are the first to address the robust quantized estimation fusion problem which deals with the uncertainties in the covariance matrix of the quantization noises. It is formulated as a minimax optimization problem which jointly optimizes the quantization levels and fusion weights.

Second, we solve the proposed robust quantized estimation fusion problem for three different correlation scenarios. The optimal solutions in Scenario (i) and Scenario (ii) are analytically derived, and that in Scenario (iii) is recast as a semidefinite programming (SDP) problem, in both singular and non-singular covariance matrix cases. The computational complexities of the related SDP problems are also analyzed.

Third, we investigate the effect of the noise correlations on the performance of the robust quantized estimation fusion. By comparing the MSEs of the robustly fused estimates in the three scenarios, we find out that if all noise components are positively (or negatively) correlated, then the resulted MSE in Scenario (ii) is larger (or smaller) than that in Scenario (i). With full knowledge of the correlations in Scenario (iii), the corresponding MSE is asymptotically smaller than that in Scenario (ii).

Fourth, numerical simulations are carried out to verify the theoretical analysis. Moreover, we demonstrate the performance of the proposed robust quantized estimation fusion method through Monte Carlo simulations, and the results indicate our method is much more robust than the quasi-BLUE estimation fusion method.

This paper is organized as follows. Section 2 is the statement of the decentralized estimation problem with probabilistic quantization strategy and energy constraint. Section 3 formulates the robust decentralized estimation fusion problem in energy-constrained WSNs. Furthermore, the formulation is equivalently converted to a maximal optimization problem. Section 4 exploits the effect of correlations among observation noises and discusses the corresponding optimal solutions for the three scenarios. Numerical simulations are provided in Section 5. Section 6 gives some concluding remarks.

Throughout this paper, for a matrix $\mathbf{X} \in \mathbb{R}^{m\times n}$, $\mathbf{X}'$ denotes its transpose, and $\mathbf{X} \succeq \mathbf{0}$ ($\succ \mathbf{0}$) means that $\mathbf{X}$ is symmetric and positive semidefinite (positive definite). For two matrices $\mathbf{X}$ and $\mathbf{Y}$, $\mathbf{X}\odot\mathbf{Y}$ represents their element-wise multiplication. The symbol $\mathbf{1}$ is the vector with all elements being 1 with appropriate dimension, the symbol $\mathbf{0}$ represents the zero matrix with appropriate dimension, and the notation $\mathbb{E}(\cdot)$ denotes the mathematical expectation of some random variable.

2. Problem statement

We consider a WSN consisting of N distributed sensors linked with an FC. Each sensor can observe, quantize and transmit its observation to the FC that estimates the unknown deterministic parameter θ based on the received messages. In practical applications, θ can be the temperature, humidity or other physical parameters that the WSN system needs to monitoring. Suppose $[-T,\ T]$ is the physical range of the unknown parameter θ, which is always available in advance as a priori information.

The local sensor observation on θ corrupted by a additive noise is described as

$$x_i = \theta + n_i, \quad i = 1, 2, \ldots, N.$$

We assume that the observation noises n_i are mean zeros and variances σ_i^2 ($i = 1, 2, \ldots, N$), and cross-correlated with covariance matrix $\mathbf{C}$. We further assume that n_i has a finite range $[-V,\ V]$ because of the limit energy of noise. A prior knowledge of the range bound V and the noise variance σ_i^2 can be determined by the physical mechanism or estimated from a sample via a training phase. Given the bounded nature of θ and n_i, it follows that x_i is bounded to be within $[-2U,\ 2U]$ for all i, where $U = (T + V)/2$.

In practical applications, due to the energy and bandwidth limitations in communication links between the sensor nodes and the FC, each sensor has to perform a local quantization of x_i and send a discrete quantized message $m_i(x_i)$ to the FC. The FC then combines the received quantized messages to generate a final estimate $\hat{\theta}$ of the parameter θ. This decentralized estimation scheme is depicted as Fig. 1.

In this paper, we adopt a probabilistic quantization scheme [9,19] due to its attractive statistical properties. The probabilistic quantization of sensor observation x_i with b_i bits is summarized as follows: dividing $[-2U,\ 2U]$ uniformly into $2^{b_i} - 1$ intervals with length $\Delta_i = (4U)/(2^{b_i} - 1)$, and round x_i to the neighboring endpoints of these small intervals in a probabilistic manner. More specifically, suppose $x_i \in [-2U + k\Delta_i, -2U + (k+1)\Delta_i)$, where $0 \le k \le 2^{b_i} - 2$, then x_i is quantized to $m_i(x_i)$ with probability distribution