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Recursive filtering for discrete-time linear systems with fading measurement and time-correlated channel noise[☆]

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ABSTRACT

This paper is concerned with the recursive filtering problem for discrete-time linear systems with fading measurement and time-correlated channel noise. The phenomenon of measurement fading appears in a random way and the fading phenomenon for each sensor is described by an individual random variable taking a value in a given interval. The time-correlated channel noise is depicted as a linear system model with white noise. Using the measurement differencing method and some results obtained in this paper, a recursive filtering algorithm for the system under consideration is proposed. The proposed algorithm is optimal in the sense of linear minimum mean-square error and does not increase computation and storage load with time. Computer simulations are carried out to evaluate the performance of the proposed algorithm.

1. Introduction

In recent years, the networked control systems (NCSs) have received wide attention due to its extensive application domains such as space and terrestrial exploration, remote diagnostics and troubleshooting, aircraft, communication, etc. In NCSs, random time-delay and packet dropouts (or fading measurements) are common in data transmission through the communication networks. Hence, the received signals via the communication networks may be imperfect.

In control engineering, many relative problems were studied for this class of systems. For such systems, a large amount of work has been devoted to studying control and stabilization problems [1–5]. The quantized H_∞ control problem for nonlinear stochastic time-delay systems with missing measurements was investigated in [1], and the optimal LQG control for discrete-time linear systems with packet dropouts was dealt with in [2]. In [3], optimal power control problem for wireless control systems was studied. The stochastic stability problem for nonlinear systems affected by random packet dropouts and delays was considered in [4], and an analytic proof of global exponential stability for multiple-input–multiple-output NCSs was provided in [5].

The state estimation problem for NCSs is a fundamental issue in all those cases and has received much research interest in recent years. The existing results are mainly concerned with the issue of data transmission time-delays and packet dropouts. In [6–8], the state estimation problem for systems with only time-delays was considered. Based on the H_∞ and L_2–L_∞ performance indexes, the filters were designed through a delay-dependent approach in [6]. In [7,8], the state estimation problem was considered in the sense of linear minimum mean-square error where the delay time considered in [7] is random and one-step random delay driven by a homogeneous Markov chain was considered in [8]. The state estimation problem for NCSs with packet dropouts was investigated in [9–11], and the filtering problem for NCSs influenced by both time-delays and packet dropouts was studied in [12–14].

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Fading measurements are now well known to be one of the most often occurred phenomena in NCSs [15–17]. This is because perfect transmission in wireless sensor networks is not always obtainable. It is obvious that the packet dropouts are extreme circumstances of the fading ones when the fading measurements decay to zero. The recursive filtering problem with fading measurements has drawn a lot of research interest in the last few years [15,17]. In [15], the authors considered a class of discrete-time linear systems with fading wireless channels. However, the channel noise considered in [15] must be white. In [17], the recursive filtering problem for systems with random parameter matrices, multiple fading measurements and correlated noises was investigated and an unbiased filter was designed. However, the correlated noises considered in [17] are only correlated on a finite time interval.

Apart from [17], many results have been reported on the state estimation problem of systems with time-correlated noise. In [18–22], the state estimation problem for discrete-time linear systems was considered where the noises considered in [18,19] are finite-time correlated and arbitrarily correlated, respectively. In [20–22], the optimal state estimation problem was tackled when the time-correlated measurement noise is described by a linear system model with white noise. As a result, two methods has been proposed to solve this problem. The first method augments the state vector by including the correlated error terms [20]. However, the method increases the dimension of the state vector and yields an ill-conditioned system [20,21]. The second method utilizes measurement differencing to remove the time-correlated portion of the measurement noises [20,22]. In [23], an optimal filter for discrete-time linear systems with multiplicative and time-correlated additive measurement noises was designed. More recently, the state estimation problem for NCSs with time-correlated noise has drawn great research interest [24–27]. For example, a robust non-fragile Kalman-type recursive filter for a class of uncertain systems with finite-step autocorrelated measurement noises and multiple packet dropouts was designed in [24] and a recursive algorithm was developed in [27] to solve the gain-constrained filtering problem for a class of time-varying nonlinear stochastic systems with probabilistic sensor delays and correlated noises. Unfortunately, these literatures about time-correlated noise presented in [18–27] do not consider the case of fading measurements. To the best of the author's knowledge, the recursive filtering problem for discrete-time linear systems with fading measurement and time-correlated channel noise described by a linear system model with white noise has not been fully studied. In practical engineering, the channel noise is often time-correlated and can be modeled as a linear system model with white noise. When fading measurement and time-correlated channel noise described by a linear system model with white noise appear simultaneously, the existing results do not fully consider. This often leads to poor performance. Therefore, it is imperative to study the filtering problem for discrete-time linear systems with fading measurement and time-correlated channel noise described by a linear system model with white noise.

In this paper, the recursive filtering problem for discrete-time linear systems with fading measurement and time-correlated channel noise is considered. The fading measurements are more general than the packet dropouts. The time-correlated channel noise is the output of a linear system model with white noise. The main contributions of this paper lie in the following aspects: (1) A recursive filtering algorithm for the system under consideration is proposed. (2) The proposed algorithm is optimal in the sense of linear minimum mean-square error (MMSE), and, using statistical property and Hadamard product, an auxiliary lemma (Lemma 3) is proved to facilitate the algorithm development. (3) The new algorithm is finite-dimensionally computable and does not increase computational and storage load with time. Hence, the new algorithm is feasible for online applications.

The rest of this paper is organized as follows. In Section 2, the recursive filtering problem under consideration is formulated, and auxiliary lemmas are presented. A recursive filtering algorithm for the system under consideration is proposed in Section 3, which is optimal in the sense of linear MMSE. In Section 4, a target tracking example is provided to demonstrate the performance of the proposed filtering algorithm. Concluding remarks are offered in Section 5.

2. Problem formulation and auxiliary lemma

Consider the following system

$$x_{k+1} = A_k x_k + \omega_k, \tag{1}$$
$$y_k = C_k x_k + \upsilon_k, \tag{2}$$
$$\breve{y}_k = \Psi_k y_k + \eta_k, \tag{3}$$
$$\eta_{k+1} = H_k \eta_k + \varepsilon_k, \quad k = 0, 1, \ldots \tag{4}$$

where $x_k \in \mathrm{R}^n$ is the unknown state; $\omega_k \in \mathrm{R}^n$ is the process noise; $y_k \in \mathrm{R}^p$ is the measurement which is sent over a fading wireless channel to a remote estimator; $\breve{y}_k \in \mathrm{R}^p$ is the information received by the estimator; $\upsilon_k \in \mathrm{R}^p$ is the measurement noise; $\eta_k \in \mathrm{R}^p$ is the channel noise; A_k, C_k and H_k are matrices of appropriate dimensions; the initial channel noise η_0 is a random vector with mean $\bar{\eta}_0$ and covariance matrix $\bar{P}_0^{\eta}$; the initial state x_0 is a random vector with mean $\bar{x}_0$ and covariance matrix $\bar{P}_0^{x}$. $\Psi_k = \mathrm{diag}\left(\psi_k^{(1)}, \psi_k^{(2)}, \ldots, \psi_k^{(p)}\right)$ where $\psi_k^{(i)},\ i = 1, 2, \ldots, p$, takes a value in a given interval $[\alpha_k, \beta_k]$ $(0 \le \alpha_k \le \beta_k \le 1)$ regulating the probabilistic fading phenomenon of the ith sensor.

We now have four assumptions.

1. ω_k, υ_k and ε_k are zero-mean white noise sequences with covariance matrices Q_k, R_k and S_k, respectively.