Signal Processing 94 (2014) 163–173

Contents lists available at ScienceDirect

Signal Processing

journal homepage: www.elsevier.com/locate/sigpro

Covariance-based estimation algorithms in networked systems with mixed uncertainties in the observations

R. Caballero-Águila [a,*], A. Hermoso-Carazo [b], J. Linares-Pérez [b]

[a] Departamento de Estadística e I. O., Universidad de Jaén, Paraje Las Lagunillas s/n, 23071 Jaén, Spain

[b] Departamento de Estadística e I.O., Universidad de Granada, Campus Fuentenueva s/n, 18071 Granada, Spain

ARTICLE INFO

Article history:
Received 11 September 2012
Received in revised form
2 June 2013
Accepted 24 June 2013
Available online 6 July 2013

Keywords:
Least-squares estimation
Covariance information
Uncertain observations
Random delays
Packet dropouts

ABSTRACT

In this paper a new observation model is proposed for networked systems subject to three sources of uncertainty. On the one hand, the measured outputs can be only noise (uncertain observations) and, on the other hand, one-step delays or packet dropouts may occur randomly during transmission; it is assumed that, at each sampling time, it is not known if some of these uncertainties have occurred. The random uncertainties are modelled by sequences of Bernoulli random variables. Under these assumptions, recursive least-squares linear estimation algorithms are derived by an innovation approach, without requiring knowledge of the signal evolution equation, but only the covariances of the processes involved in the observation model and the uncertainty probabilities.

1. Introduction

In networked systems, the measured output is transmitted to a processing center producing the signal estimation. The unreliable network characteristics can produce uncertain observations (measured outputs containing noise only) and, moreover, random delays and/or packet dropouts can occur during transmission due to different causes, such as random failures in the transmission mechanism, accidental loss of some measurements or data inaccessibility at certain times. Several results on this area have been reviewed in the survey paper [1].

Under these sources of uncertainties, standard observation models are not appropriate and modifications of the estimation algorithms are necessary to accommodate their effect. Estimation problems considering only one of the aforementioned uncertainties have been widely studied in the literature; next, a brief review about some of the existing results is presented.

In most classical literature concerning to the signal estimation problem, it is assumed that the measured output always contains the real signal contaminated by external disturbances. However, in practical applications such as target tracking, there may be a positive probability that any observation consists of noise only if the target is absent and, hence, the measured output does not contain information on the signal to be estimated; this failure can be caused by many different reasons, such as high manoeuverability of the tracked target, intermittent failures in the observation device, and data inaccessibility during certain times. These kinds of situations have been considered by several authors. For example, motivated by navigation and tracking applications within sensor networks, Sinopoli et al. [2] consider the Kalman filtering problem with intermittent observations in order to avoid the information loss in the control loop when the data are transmitted along unreliable communication channels in a large, wireless, multihop sensor network. Rapoport and Oshman [3] analyze situations involving a simple global

* Corresponding author. Tel.: +34 953 21 29 26; fax: +34 953 21 20 34.
E-mail addresses: raguila@ujaen.es (R. Caballero-Águila), ahermoso@ugr.es (A. Hermoso-Carazo), jlinares@ugr.es (J. Linares-Pérez).

0165-1684/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.sigpro.2013.06.035

positioning system (GPS)-aided navigation system, where the GPS measurements are fault-prone due to their sensitivity to multipath errors. Imer et al. [4] consider situations that demand remote control of objects over internet-type or wireless networks, where links are prone to failure. All these situations are characterized by the fact that the signal appears randomly in the observations. More specifically, there is a positive probability (false alarm probability) that the signal to be estimated is not present in the corresponding observation; that is, some observations may be only emissions of noise. These systems, called *systems with uncertain observations* or *systems with missing measurements*, are modelled by including not only additive noise in the measurements, but also a multiplicative binary process described by a sequence of Bernoulli variables; specifically, if z_k represents the observation at time k, it is related to the signal x_k by the following equation:

$$z_k = \gamma_k H_k x_k + v_k, \quad k \geq 1,$$

where v_k is the observation noise and γ_k is the Bernoulli variable whose values, zero or one, describe the possible absence of signal x_k at the observation z_k.

Using a state-space approach, Nahi [5] was the first to study the optimal linear recursive filtering problem in discrete-time systems with uncertain observations, assuming independence in the uncertainty. Later on, this problem has been widely studied using both the state-space model of the signal (see e.g. [6,7] and references therein) and covariance information (see e.g. [8,9] and references therein) under different hypotheses on the additive and multiplicative noises involved in the system equations. In the above papers, Bernoulli random variables are used to model the missing measurements phenomenon and, hence, the information about the signal x_k is either completely transmitted (when $\gamma_k = 1$) or completely lost (if $\gamma_k = 0$). Recently, this missing measurement model has been generalized considering any discrete distribution on the interval $[0, 1]$, which allows us to cover some practical applications where only partial information is missing (see [10,11] and references therein).

On the other hand, the increasing use of communication networks for transmitting data motivates the need for considering possible transmission delays causing that the data available for the estimator are not updated and/or producing possible packet losses. It is well known that network delay and data transmission loss exist in many practical systems and they are often a primary source of instability and performance degradation.

Systems with time delays have received much attention in the past few decades, since this kind of failure commonly exists in many real-world applications, such as hydraulic processes, chemical systems, and temperature processes. Under the assumption that the observation packets are received either immediately or with a known deterministic delay, many effective estimation techniques have been developed. However, in certain newly arisen engineering applications, such as under-water acoustic or mobile communications and exploration seismology, the observations are need to be transmitted through communication channels which may induce considerable, irregular and randomly varying transmission delays. Some examples are remote control of a large number of mobile units, complex networked sensor systems containing a large number of low power sensors, as well as complex dynamical processes like advanced aircraft, spacecraft, and manufacturing process, where time division multiplexed networks are employed for exchange of information between spatially distributed plant components [12]. Therefore, in several applications the delays occur in a random way, rather than a deterministic way, and they should be interpreted as a stochastic process, including its statistical properties in the system model. The interest on the estimation problem in *systems with randomly delayed observations* has been increasing during the past few years, and attention has been mainly focused on estimation from measurements subject to random delay which does not exceed one sampling period; that is, the available observation at any time is assumed to be either the current measurement or the previous one, and the delays are modelled by zero-one variables indicating if the measurements are delayed or arrive on time. Specifically, if $\{\zeta_k; k \geq 1\}$ denotes a sequence of Bernoulli variables, and a delay at time k is identified with the event $\zeta_k = 0$, the available measurements for the estimation are given by

$$y_k = \zeta_k z_k + (1 - \zeta_k) z_{k-1}, \quad k \geq 1.$$

Ray et al. [13] were the first who modified the conventional algorithms to fit this observation model and, later on, many results have been reported, using both the state-space model of the signal and covariance information (see, among others, [14,15] and references therein). Although this formulation implies that some measurements might never be used for the estimation, it has been shown to be appropriate to model different practical situations, as pointed out, for example, in [16,17].

Another key issue arising in networked systems is the problem of data packet dropout, which happens due to the limited bandwidth and unreliable transmission over one line. Stochastic packet dropouts are very common in large-scale networks and when network becomes congested. In practical networked systems, the common network protocols specify that when a data packet does not arrive at a destination in a certain transmission time, it means that this data packet is lost. For widely used transmission control protocol, the packet is declared loss if it has not been received correctly after a certain time period, that is, dropped packets are present after a certain number of transmission delays. Over the past few years, research on *systems with packet dropouts* has gained a lot of interest due to the applications of networks in communication systems, control systems and signal processing, among others. When a packet is dropped out, we do not have a valid packet for processing and a common approach is to retain the previous packet; hence, random packet losses can be described according to a Bernoulli process, that is, by introducing zero-one random variables indicating if the current measurement is available or lost (in which case the latest measurement is processed). More specifically, if $\{\varphi_k; k \geq 1\}$ are Bernoulli variables, the measurements processed are described by

$$y_k = \varphi_k z_k + (1 - \varphi_k) y_{k-1}, \quad k \geq 1.$$