Optimal estimation in networked control systems subject to random delay and packet drop

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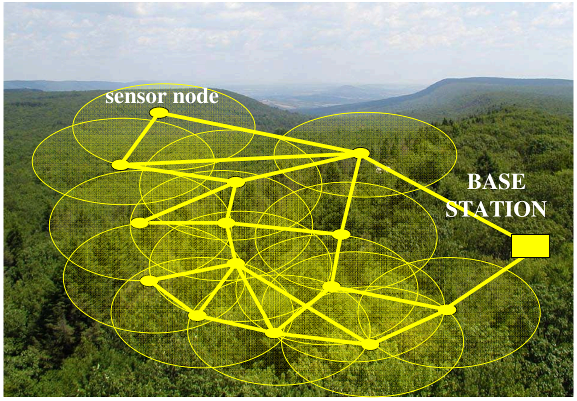
Abstract

In this paper we study optimal estimation design for sampled linear systems where the sensors measurements are transmitted to the estimator site via a generic digital communication networks. Sensor measurements are subject to random delay or might even be completely lost. We show that the minimum error covariance estimator is time-varying and stochastic which does not converge to a steady state. Moreover this estimator can be implemented using a finite memory buffer if and only if the delivered packets have a finite maximum delay and it is independent of the communication protocol. We also present two alternative estimator designs alternative estimator architectures which adopt constant gain, and, surprisingly, we show that stability does not depend on packet delay but only on the packet loss probability which must be sufficiently small. Finally, algorithms to compute critical loss probability and estimators performance in terms of error covariance are given and applied to some numerical examples.

I. Introduction

Recent technological advances in MEMS, DSP capabilities, computing, and communication technology are revolutionizing our ability to build massively distributed networked control systems (NCS) [1]. These networks can offer access to an unprecedented quality and quantity of information which can revolutionize our ability in controlling of the environment, such as fine grane building environmental control [2], vehicular networks and traffic control [3], and surveillance and coordinated robotics [4]. However, they also present challenging problems arising from the fact that sensors, actuators and controllers are not physically collocated and need to exchange information via a digital communication network. In particular, measurement and control packets are subject to random delay and loss. These problems are particularly evident in wireless communication networks which are rapidly replacing wired communication infrastructures in many engineering areas [5]. This is because wireless systems are easier and cheaper to deploy and avoids cumbersome cabling and positioning. Besides, new technologies like wireless sensor networks (WSNs), which are large networks of spatially distributed electronic devices, known as nodes, capable of sensing, computation and wireless communication, will enable the development of applications previously unfeasible [6] [7]. For example, WSN has been used for animal habitat monitoring in inhospitable regions [8] and microclimate monitoring in forests [9]. These are typical example of large scale fine grain sensor data-collection applications where are information is collected and then analyzed off-line.

However, WSN are going to be employed also for real-time applications. For example consider a WSN deployed in a forest whose nodes are equipped with temperature and humidity sensors, as graphically shown in the left panel of Fig. 1. The same network could be used to monitor climate variations (data-collection application) or for wild-fire detection and tracking (real-time application) [10]. Despite the fact that these two applications adopt the same infrastructure, they obviously have different packet delay and packet loss requirements, which are shown as shaded regions in right panel of Figure 1. In fact, in data-collection applications it is important only to extract all data regardless of their delay, while in real-time control applications both delay and packet loss are important. Unfortunately, it is well known that when designing communication protocols for communication networks there are unavoidable tradeoffs between packet loss and packet delay. In fact, communication protocols that reduce packet loss require retransmission of lost packets and packet delivery acknowledgment, which increase traffic and consequently delay. Viceversa reducing time delay requires dropping of packets to reduce traffic and



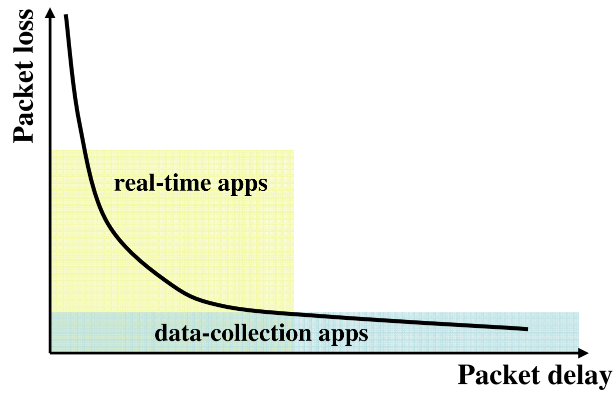


Fig. 1. Pictorial representation of Wireless Sensor Network for forest monitoring or wildfire detection *(left)*. Tradeoff curve typical of many network communication protocols and constraint regions for real-time and data-collection applications *(right)*.

packet collisions (see solid line in left panel of Fig. 1). Therefore, it is not trivial to design communication protocols for control systems since both delay and packet loss negatively impact estimation and closed loop performance of controlled systems, and they can even lead to instability. Currently, communications protocols and networked control systems are designed separately. In particular, protocols are design based on conservative heuristics which specifies what the maximum time delay and maximum packet loss should be, but with no clear understanding of their impacts on the overall application performance. On the application side, control systems are not specifically designed to exploit information about packet loss and delay of the communication protocols they will run on. From these observations some questions arise. For example, how should we design estimators and networked systems that take into account simultaneous random delay and packet loss? How can we estimate their performance? When is the closed loop system stable? How can we chose between a communication protocol with a large packet delay and a small packet loss and a protocol that have a small packet delay and a large packet loss for best performance of a specific real-time application? These are the questions that motivate this work.

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