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Optimal Control of Energy Resources for State Estimation Over Wireless Channels

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Chapter 1
Introduction

Recent years have seen increasing use of wireless technologies in diverse applications such as in environment monitoring, health care, and industrial monitoring and control. The convenience and cost savings due to the elimination of the need for wiring are readily apparent, for instance, the ease nowadays of setting up wireless networks in the home. Due to advances in micro-electro-mechanical technology, small and low-cost sensors with sensing, computation and wireless communication capabilities have become widely available. Such wireless sensors and actuators can be placed where wires cannot go, or where power sockets are not available. With this technology, ecosystems such as the Great Barrier Reef in Australia can be continuously monitored for pollution and to study the effects of climate change [1]. In health care, different body parts of a patient can be remotely monitored and doctors alerted if more medication or treatment is required [2].

New technologies such as cyber-physical systems [3, 4], smart cities [5, 6] and the Internet of Things [7, 8] have been envisioned, where many everyday objects are connected together (and also to the Internet) to form a network, potentially bringing further improvements to the quality of life. For example, using the location information of vehicles in the city can allow for improved traffic flow, alert drivers to areas of congestion and optimize the traffic light patterns for public transport. Autonomous vehicles, which will soon be available to the general public, can potentially lead to fewer accidents and increased traffic capacity. Buildings can be made more energy efficient by using more sophisticated control of the heating and cooling, ventilation and lighting, e.g. by using information on people's behaviour. Infrastructure such as water distribution networks can be continuously monitored, such that faults are detected and attended to quickly, leading to less wastage of resources. Air quality can be monitored with high resolution, alerting citizens and authorities when needed. In all these cases, communication with other sensors/devices or central authorities will be mainly over wireless channels.

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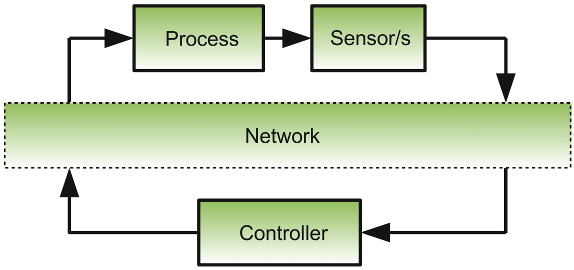
Fig. 1.1 Networked control system



Networked Control Systems

In industrial monitoring and control applications, the driving force behind using wireless technology is its lower deployment and reconfiguration cost. Here, reliable operation is of vital importance, as a delay in implementing appropriate feedback control actions can drive a dynamical system to instability and cause substantial damage (both physical and financial). Nonetheless, even in such mission critical domains, the use of wireless technologies has become more prevalent, with industrial wireless sensor networks standards such as WirelessHART [9] being developed.

This has motivated significant research into networked control systems [10–13], where measurement and control signals are transmitted over channels (e.g. fading channels) or networks, see Fig. 1.1. In addition to bit rate limitations, these channels/networks introduce effects such as packet drops and delays. Research in networked control systems has included the derivation of conditions for stability and stabilizability, and methods for designing estimators and controllers which have a degree of robustness, in the presence of such effects. To derive these results, often the wireless environment has been abstracted into stochastic models such as i.i.d. (or Markovian) packet dropping links or regarded fading as multiplicative noise, which are then studied using mainly control-theoretic techniques. However, our view is that techniques and ideas from wireless communications itself, such as how to optimally manage energy resources in the presence of fading, can also be effectively utilized in the study and design of networked control systems. This book aims to demonstrate that making use of these additional techniques can provide significant performance gains.

Wireless Communications

Wireless channels, also known as fading channels, are inherently randomly time-varying, due to the small-scale effect of multipath, and larger scale effects such as path loss and shadowing by obstacles [14]. This can cause the transmitted signals to be attenuated, distorted, delayed or lost in ways which are difficult to predict, see Fig. 1.2. Signals transmitted by different sensors/devices over the wireless medium can also interfere with each other. Maintaining acceptable quality of service in such conditions is a challenging problem. Nevertheless, the goal of communicating with high reliability at ever higher data rates has been pursued extensively by the wireless

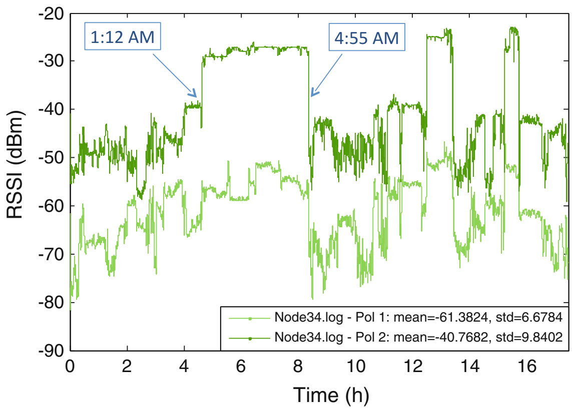


Fig. 1.2 Channel measurements taken at a paper mill [15]

communications community over the last 30 years, and many novel ideas have been developed.

In particular, power control is a key enabling technology for wireless communications. It serves to compensate for the time-varying channel gains, to provide quality of service guarantees to users and also to increase spectral efficiency [14]. Energy harvesting technologies [16, 17], where the sensor can recharge their batteries by extracting energy from the surrounding environment, can dramatically increase the lifetime of nodes in wireless sensor networks, and will be fundamental in the implementation of self-sustaining cyber-physical systems and the Internet of Things. Coding schemes can improve the reliability of the transmitted information, with network coding even able to increase throughput [18, 19]. Multi-hop networks and cooperative communications via the use of relays [20] have been identified as some of the key enabling technologies for fifth generation (5G) mobile networks [21]. These ideas, just to name a few, have not received much attention in the study of networked control systems so far, while we believe that they can, and should, be fruitfully utilized.

Contributions and Scope of This Book

One of the goals of this book is to bring closer together the wireless communications and control literature, by introducing wireless communications techniques and ideas into the study and design of networked control systems. For that purpose, the focus is on state estimation problems where sensor measurements (or related quantities such as local state estimates or innovations) are transmitted over wireless links to a central observer, see Fig. 1.3. State estimation of dynamical systems is important in areas such as environment monitoring and tracking. Furthermore, estimated state feedback control forms a central part of contemporary control systems [22]. Indeed, some of the topics studied in this book have also been extended to feedback control [23–26].

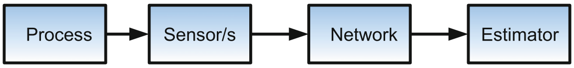


Fig. 1.3 Networked estimation

The approach taken in this book is to utilize some of the techniques and ideas that have been developed in wireless communications for energy[1] resource management, in order to improve the performance of the estimator when transmission occurs over wireless packet dropping links. Many previous works have studied Kalman filtering and control over packet dropping links, but where the energy usage is not explicitly taken into account [27, 28]. Some works in the networked estimation and control literature have considered fading [29–33], but apart from [32] the fading is often treated as unknown multiplicative noise. This can lead to conservative designs, since in practice, often knowledge of the fading channel gains is available[2] at the receiver (or transmitter). Thus, in this book, we will assume that the fading channel gains are known and can be exploited, e.g. by using power control [14] to enhance system performance.

Energy harvesting based rechargeable batteries or storage devices can offer significant advantages in the deployment of large-scale wireless sensor and actuator networks. These devices, when integrated into the sensor/actuator nodes, provide freedom from the task of periodically having to replace batteries, and open the possibility for sensors to operate in a self-sustaining manner. Recent research on energy harvesting has largely focused on resource allocation for wireless communication systems design, optimizing communication objectives such as maximizing throughput or minimizing transmission delay [35–37]. In contrast, in this book, we directly optimize estimation objectives such as minimizing the expected estimation error covariance.

This book focuses on performance optimization of networked estimation systems, which goes beyond the notion of stability/stabilizability considered in many papers. As mentioned previously, two fundamental aspects in wireless communications are fading and interference [14]. In this book, we directly deal with fading, while interference is indirectly dealt with in our formulation via the particular abstraction of packet loss that can consider interference by using higher packet loss probabilities. In terms of robustness issues, our work in power control addresses robustness with respect to the time-varying behaviour of the fading channels. However, robustness in terms of model imperfections lies beyond the scope of this book and will not be considered.

Book Outline

Chapter 2 deals with power allocation for state estimation of discrete-time linear dynamical systems. The sensors transmit measurements over a packet dropping channel, where the probability of successful packet reception is time-varying and

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[1] We measure energy on a per channel use basis and will refer to energy and power interchangeably.

[2] In wireless communication, this is referred to as having channel state information at the receiver or transmitter [34].

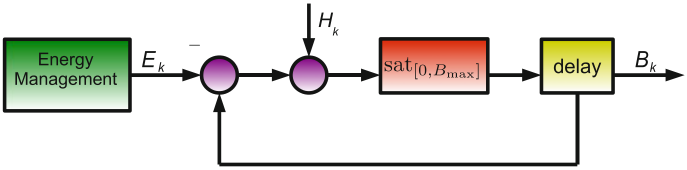

Fig. 1.4 Energy harvesting

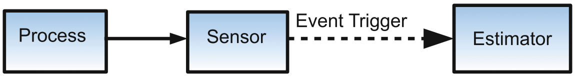

Fig. 1.5 Event triggered estimation

depends on the instantaneous fading channel gain and transmit power used. We first consider a transmission power control problem to minimize a linear combination of the expected error covariance and expected energy usage. We then study an optimal transmission power control problem where energy is randomly harvested from the environment. Here, the transmission energy is constrained by the battery level (which depends on the energy used in previous time steps and the energy harvested in the meantime), see Fig. 1.4.

Chapter 3 considers event-triggered estimation, see Fig. 1.5, where a sensor will transmit local state estimates to a remote estimator only when certain events occur, e.g. if the estimation quality has deteriorated sufficiently. This can save energy while still maintaining a certain level of performance. In particular, we study the case where the transmission decisions are obtained from the solution to an optimization problem that minimizes a linear combination of the expected error covariance and expected energy usage. We derive structural results which show that the optimal policy is of threshold type, i.e. transmit if and only if the error covariance at the remote estimator exceeds a certain threshold. This provides a rigorous justification of variance-based threshold policies proposed in [38]. We then consider the problem of minimizing the expected error covariance subject to energy harvesting constraints, where a transmission can occur only if there is sufficient energy in the battery. We show that the optimal policies have a threshold structure in both the error covariance and the battery level.

Chapter 4 studies a design problem which arises in the context of optimal transmission strategies for remote state estimation. We consider the case where a sensor can either transmit its local state estimate or its local innovations. While transmitting local estimates will give improved performance at the remote estimator, often it will also have a larger variance and require more energy to transmit. This raises the issue of finding a transmission strategy that optimizes a linear combination of the expected error covariance and expected energy usage. For scalar systems, it turns out that (similar to Chap. 3) the optimal strategy also has a threshold structure, where one transmits the estimates if the error covariance exceeds a certain threshold, and transmits the innovations otherwise.

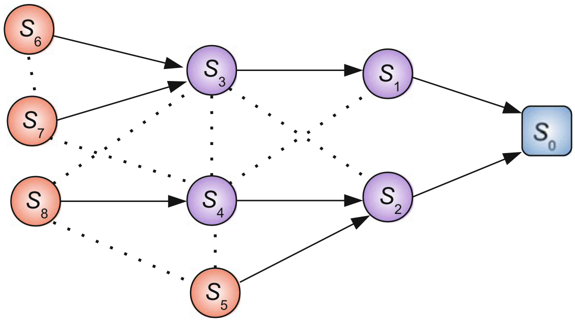

Fig. 1.6 Multi-hop network

Chapter 5 focuses on remote state estimation problems over multi-hop networks, see Fig. 1.6. Here, we show that performance benefits can be obtained if one adopts more advanced communication techniques such as network coding [18, 19], relays [20], and rerouting [39]. We first consider a set-up where sensors can transmit both directly to the remote estimator or via intermediate relays. We consider different operations that the relay can perform such as forwarding of transmissions or network coding operations, and optimize over the relay operations and transmission powers. Next, we consider the problem of reconfiguring the topology of (or *rerouting*) a multi-hop network, in order to respond to time variations in the wireless channel conditions. Optimal and suboptimal methods for reconfiguring the network are proposed, and their performance compared.

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