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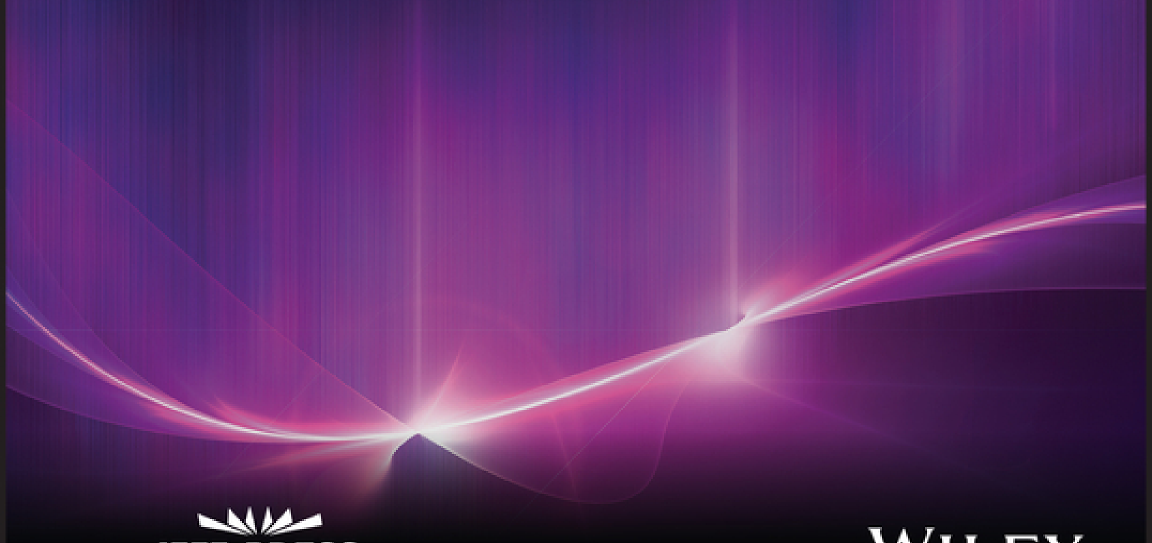
Control over Communication Networks

Modeling, Analysis, and Design of Networked Control Systems and Multi-Agent Systems over Imperfect Communication Channels



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To my parents, my husband Pengfei, and my daughter Coco (Jianying Zheng)
To my parents, my wife Xiaoxue, and my son Ze (Liang Xu)

Contents

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Jianying Zheng received the BE degree in Automation from University of Science and Technology of China in 2010, and the PhD degree in Electronic and Computer Engineering from the Hong Kong University of Science and Technology, Hong Kong, in 2016. Between September 2014 and February 2015, she was a visiting student in the University of Newcastle, Australia. From 2016 to 2018, she worked as a Research Fellow in the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. Since 2018, she joined Beihang University, where she is currently an associate professor. Her current research interests include networked control systems, multi-agent systems, and spacecraft formation control.

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His research interests include the design and control of spacecraft attitude system and fault tolerant control to aerospace engineering. He has published significantly on the subjects with over 100 technical papers while enjoying the application of the theory through astronautic consulting. He has been actively involved in various technical professional societies such American Institute of Aeronautics and Astronautics (AIAA), Institute of Electrical and Electronics Engineers (IEEE) and American Society of Mechanical Engineers (ASME), as reflected by AIAA Associate Fellow, IEEE Senior Member and general chair of many international conferences. He also previously served as associate editor for Aerospace Science and Technology, etc.

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Dr. Xie's research interests include robust control and estimation, networked control systems, multi-agent networks, and unmanned systems. In these areas, he has published 9 books, over 500 journal papers, and over 20 patents/technical disclosures. He was listed as a highly cited researcher by Thomson Routers and Clarivate Analytics. In addition to fundamental research contributions, he has developed a universal navigation system for AGVs in manufacturing and logistics, patented WiFi-based technologies for indoor positioning and human activity recognitions, and reliable and accurate positioning systems for UAV-based structure inspection. He has received many awards for his research.

He is an editor-in-chief for Unmanned Systems and an associate editor for Sciences China – Information Science. He has served as an editor of IET Book Series in Control and an associate editor of a number of journals including IEEE Transactions on Automatic Control, Automatica, IEEE Transactions on Control Systems Technology, IEEE Transactions on Network Control Systems, and IEEE Transactions on Circuits and Systems-II, etc. He was an IEEE Distinguished Lecturer from 2011 to 2014.

Preface

In networked control systems (NCSs), wired or wireless communication channels are used to link components among plants, sensors, and controllers to achieve control objectives. While there are many advantages, NCSs also introduce a series of challenging problems that arise from the limited resources and unreliability of the communication networks used for information transmission. For example, due to congestion, data losses and transmission delays may occur in digital communication channels. Besides, in wireless communication networks, which are widely used in sensor networks and multi-agent systems (MASs), communication channels naturally suffer from inference, fading, and transmission noises. Since control is often used in safety or mission-critical applications, we must take the uncertainties in communication networks into consideration and investigate how they affect the stability and performance of NCSs and MASs.

The book gives a systematical and self-contained description for the analysis and design of NCSs and MASs over imperfect communication networks. Specifically, the book considers fading channels and delayed channels and includes two main parts. In the first part, the stabilization, optimal control, and remote state estimation of linear systems over channels with fading, signal-to-noise constraints, or intermittent measurements are considered. The channel requirements for the mean-square stabilization and optimal control are characterized and the optimal estimator designs and performance analysis are conducted. In the second part, the joint impact of communication channels and network topology on the consensusability of MASs is analyzed. By integrating communication and control theory, we present several fundamental results on the stabilization, optimal control, and estimation of NCSs and the consensus of MASs over imperfect channels. The book intends to provide a unified platform for introducing the analysis and design of NCSs and MASs for researchers working in related areas.

January 2023

Jianying Zheng
Liang Xu
Qinglei Hu
Lihua Xie

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The contents included in this book are the outgrowth and summary of the authors' academic research achievements on the analysis and design of networked control systems and multi-agent systems over imperfect communication channels in the past several years. Some of the materials contained herein arose from the joint work with our collaborators, and the book would not have been possible without their efforts and support. In particular, the first author is indebted to Prof. Li Qiu from the Hong Kong University of Science and Technology, who led her into the gate of scientific research. We would like to thank our collaborators, including Prof. Jiu-Gang Dong, Prof. Yilin Mo, Prof. Keyou You, Prof. Chao Yang, and Dr. Nan Xiao, for their helpful discussions, and the students Roudan Zhou and Xiao Wang for their assistance in preparing the manuscript.

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Acronyms

a.e.	almost everywhere
ARE	algebraic Riccati equation
AWGN	additive white Gaussian noise
BMI	bilinear matrix inequality
CEL	compressed edge Laplacian
CIIM	compressed in-incidence matrix
CIM	compressed incidence matrix
DEL	directed edge Laplacian
FSMC	finite-state Markov channel(s)
i.i.d.	independent and identically distributed
IIM	in-incidence matrix
IM	incidence matrix
LMI	linear matrix inequality(-ies)
LTI	linear time-invariant
LQ	linear quadratic
LQG	linear quadratic Gaussian
MARE	modified algebraic Riccati equation(s)
MAS	multi-agent system(s)
MIMO	multi-input-multi-output
MJLS	Markov jump linear system
MSE	mean-square error
MMSE	minimum mean-square error
NCS	networked control system(s)
SNR	signal-to-noise ratio
TCP	transport control protocol
TDMA	time division multiple access

List of Symbols

$\mathbb{N}$	the set of natural numbers
$\mathbb{N}^+$	the set of positive natural numbers
$\mathbb{R}(\mathbb{C})$	the set of real (complex) numbers
$\mathbb{R}^n(\mathbb{C}^n)$	the set of n-dimensional real (complex) column vectors
$\mathbb{R}^{m\times n}(\mathbb{C}^{m\times n})$	the set of $m \times n$-dimensional real (complex) matrices
$\mathcal{S}_n$	the set of $n \times n$ symmetric matrices
$\mathcal{P}_n$	the set of $n \times n$ positive semidefinite matrices
$\mathrm{Re}(c)$	the real part of $c \in \mathbb{C}$
$\|c\|$	the magnitude of $c \in \mathbb{C}$
$\|\mathcal{S}\|$	the cardinality of set $\mathcal{S}$
$\mathbf{1}$	a column vector of ones
$0_{m\times n}$	an $m \times n$ matrix with all entries being zero
I_N	the N-by-N identity matrix
A'	the transpose of matrix A
A^*	the conjugate transpose of matrix A
$[A]_{ij}$	the ijth element of matrix A
$[A]_{\mathrm{row}\, i}$	the ith row of matrix A
$[A]_{\mathrm{column}\, j}$	the jth column of matrix A
A^{-1}	the inverse of matrix A
$A^{\dagger}$	the Moore–Penrose pseudoinverse of matrix A
$\rho(A)$	the spectral radius of matrix A
$\mathrm{tr}(A)$	the trace of matrix A
$\det(A)$	the determinant of matrix A
$\mathrm{null}(A)$	the null space of matrix A
$\mathrm{diag}(A, B)$	a diagonal matrix with diagonal entries A and B
$\begin{bmatrix} A & * \\ C & B \end{bmatrix}$	the abbreviation of the symmetric matrix $\begin{bmatrix} A & C' \\ C & B \end{bmatrix}$
$\lambda_{\min}(S)$	the minimal eigenvalue of a real symmetric matrix S
$S > 0\ (S \geq 0)$	positive definite (semidefinite) matrix

χ^t	the sequence $\{\chi_i\}_{i=0}^{t}$
$\otimes$	the Kronecker product
$\odot$	the Hadamard product
$\mathbb{E}\{\cdot\}$	the expectation operator
$\mathbb{E}_x\{\cdot\}$	the expectation conditioned on the event $X = x$
$\mathcal{N}_x(\bar{x}, \Sigma)$	a random variable x with Gaussian distribution of mean $\bar{x}$ and covariance matrix Σ
$f(x)$ $(\Pr(x))$	the probability density function (probability) of the random variable x
$f(x\vert y)$ $(\Pr(x\vert y))$	the probability density function (probability) of the random variable x conditioned on the event that $Y = y$
$\mathfrak{e}$	the Euler's number
$\ln(\cdot)$	the natural logarithm
$\log(\cdot)$	the logarithm to base 2
$\log_x(\cdot)$	the logarithm to base x

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Introduction

1.1 Introduction and Motivation

1.1.1 Networked Control Systems

Due to the flexible architecture and ease of installation and maintenance, communication networks are widely used in control systems, which result in networked control systems (NCSs), where the plants, actuators, sensors, and controllers are spatially distributed and interconnected by communication channels [Schenato et al., 2007, Hespanha et al.]. NCSs are ubiquitous in industry and daily life, such as teleoperation [Arcara and Melchiorri, 2002], power systems [Wang et al., 2012], and transportation systems [Seiler and Sengupta, 2001].

Even though NCSs have the advantages of low cost, easy implementation, and expansion to large-scale applications, they also introduce new challenging problems arising from the limited resources and unreliability of the communication networks used for information transmission (see Figure 1.1). For example, the time delay may occur in digital communication channels due to data processing and transmission [Tse and Viswanath, 2005, Goldsmith, 2005]. Notably, in wireless communication networks, communication channels naturally suffer from interference, fading, and transmission noises [Tse and Viswanath, 2005, Goldsmith, 2005]. There into, fading is the time variation of channel strengths and is usually caused by two factors: one is the shadowing from obstacles; the other one is the multipath propagation [Tse and Viswanath, 2005, Goldsmith, 2005]. Packet drops can also be modeled as a special case of channel fading. Take Figure 1.2 as an illustration. The wireless signal may transmit through the car and undergo several paths before arriving at the receiver. If the phases of the received signals from different paths are the same, the signal strength is enhanced. Otherwise, the signal strength is reduced as a result of the cancellation of radio waves. Besides, the signal strength at the receiver side might be reduced due to the shadowing from

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the car. Since control is often used in safety- or mission-critical applications, we must take the uncertainties in communication networks into consideration and investigate how they affect the stability and performance of control systems.

The classical control theory mainly deals with the systems with nearly perfect point-to-point connections and focuses on the design of control laws to achieve the given control performance. It can't be applied directly to the NCSs when the uncertainties in the communication network must be considered. A new control paradigm is required to deal with the interplay between control and communication. In this book, one of the main objectives is to study the stabilization, estimation, and optimal control of NCSs over channels with fading, packet drops, or delay.

1.1.2 Multi-Agent Systems

Motivated by the collective behavior in nature, such as schooling fish, flocking birds, and marching locusts, multi-agent systems (MASs) have attracted considerable research interest from the control community [Jadbabaie et al., 2003, Olfati-Saber and Murray, 2004, Olfati-Saber et al., 2007, Bliman and Ferrari-Trecate, 2008, Cao et al., 2008, Ren and Beard, 2008, You and Xie, 2010, Cao et al., 2012, Trentelman et al., 2013, Qi et al., 2016, Qiu et al., 2017, Xu et al., 2018, Zheng et al., 2018]. With the rapid development of wireless communication networks, MASs have been applied in many industrial and military applications. Such systems usually involve large numbers of autonomous agents (e.g. robots, unmanned aerial vehicles, satellites), which share information via local interactions and work together to achieve collective objectives.

For MASs, each agent can have the same or different system dynamics, resulting in different types of MASs, e.g. first- and second-order MASs, linear and nonlinear MASs, homogeneous and heterogeneous MASs. The interactions among the agents form the interaction topology, which can be fixed or time-varying. Then the cooperative control of MASs is based on the system dynamics and the interaction topology to design the control laws, which can be centralized or distributed, to fulfill a task. Typical cooperative control tasks include consensus, formation, swarming/flocking, rendezvous, etc. There into, the consensus problem, which requires all agents to agree on a certain quantity of common interests, builds the foundation of other cooperative tasks.

Existing research on consensus assumes that the communication networks among agents are perfect. However, as mentioned earlier, in practical applications, communication channels naturally suffer from fading, signal-to-noise ratio (SNR) constraints, time delay, etc. Hence, it is of great significance to study how

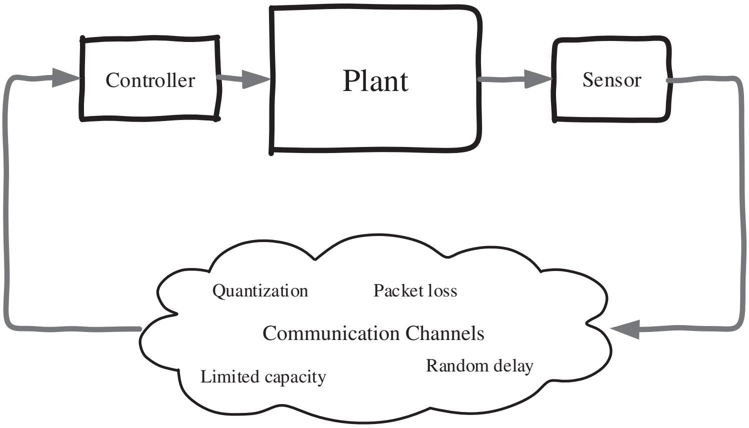

Figure 1.1 Networked control systems.

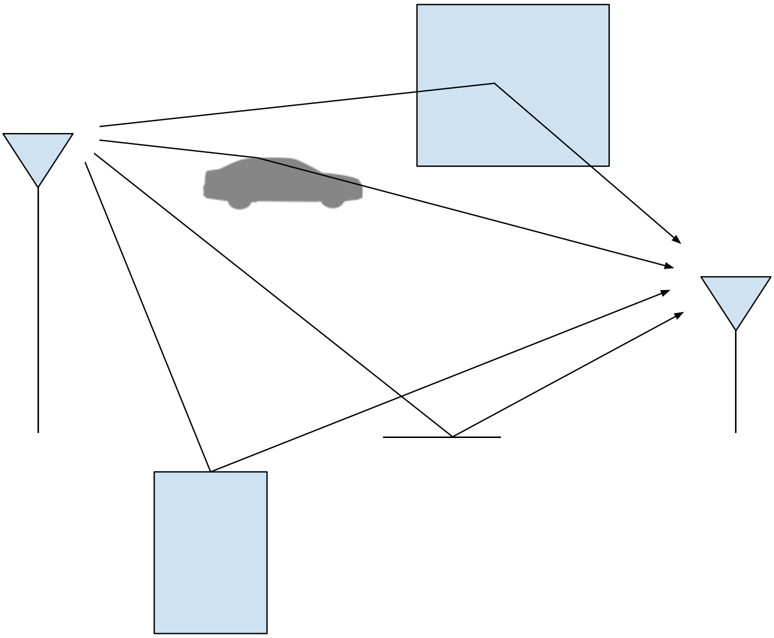

Figure 1.2 Fading phenomenon in wireless communications.

the uncertainties in communication networks influence the consensus of MASs. The other main objective of this book is to analyze the consensus problem of MASs over channels with fading, packet drops, and delay.

1.2 Literature Review

Control over communication channels/networks has been a hot research topic in the past decades [Matveev and Savkin, 2009, Como et al., 2014, You et al., 2015], motivated by the rapid developments of wireless communication technologies that enable the wide connection of geographically distributed devices and systems. However, the inclusion of wireless communication channels/networks also introduces challenges in the analysis and design of control systems due to constraints and uncertainties in wireless communications. We must take the communication channels/networks into consideration and study their impact on the stability and performance of control systems. This section briefly reviews existing results on the analysis and design of NCSs and MASs over imperfect communication channels.

1.2.1 Basics of Communication Theory

One of the main focuses of this book is to characterize the critical channel requirement such that the NCS can be mean-square stabilized. Since the communication channel is used to transmit information about the system state, as illustrated in Figure 1.1, it is expected that if the channel capacity is large enough, the feedback connected system can be mean-square stable. From this perspective, the communication channel capacity might be critical for the mean-square stabilization of control systems.

The channel capacity problem is fundamental in communication theory since it dictates the maximum data rates that can be transmitted over channels with asymptotically small error probability [Tse and Viswanath, 2005, Goldsmith, 2005]. In this subsection, we briefly review the communication channel capacity definitions and discuss why the communication theoretic channel capacity is not the critical characterization of the capacity required for controls. We only discuss discrete memoryless channels, and most of the definitions are borrowed from Cover and Thomas [2006].

A discrete memoryless channel consists of three parts: an input alphabet $\mathcal{X}$, an output alphabet $\mathcal{Y}$, and a probability transition matrix $p(y|x)$ that describes the probability of observing the output symbol y given the input symbol x. The channel is memoryless if the probability distribution of the current channel output conditioned on the current channel input is independent of previous channel inputs or outputs. The configuration of the point-to-point communication system

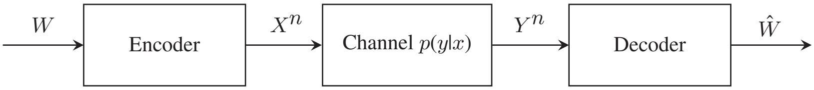

Figure 1.3 Point-to-point communication system.

is depicted in Figure 1.3. We want to transmit a message W reliably through the communication channel with appropriately designed channel encoders and decoders. The (M, n) code in a communication system is defined as follows.

Definition 1.1 ***((M, n) code)*** An (M, n) code for the channel $(\mathcal{X}, p(y|x), \mathcal{Y})$ consists of three parts:

1. A message index set $\{1, 2, \ldots, M\}$.
2. An encoding function $X^n : \{1, 2, \ldots, M\} \to \mathcal{X}^n$, generating codewords $x^n(1)$, $x^n(2)$, …, $x^n(M)$.
3. A decoding function $g : \mathcal{Y}^n \to \{1, 2, \ldots, M\}$, generating an estimate for the transmitted message index.

The performance of the code is measured by the decoding error.

Definition 1.2 ***(Decoding error)*** The maximal probability of error for an (M, n) code is defined as $\lambda^{(n)} = \max_{i \in \{1,2,\ldots,M\}} \Pr(g(Y^n) \neq i | X^n = x^n(i))$.

The communication channel capacity which measures the maximal capacity for reliably transmitting the information is defined below.

Definition 1.3 ***(Channel capacity)*** The rate R of the (M, n) code is defined as

$$R = \frac{\log M}{n} \text{ bits per transmission.}$$

A rate R is achievable if there exists a sequence of $(\lceil 2^{nR} \rceil, n)$ codes such that $\lambda^{(n)}$ tends to 0 as $n \to \infty$. The channel capacity C is then defined as the supremum of all achievable rates.

The channel capacity in Definition 1.3 is called the Shannon channel capacity since C. E. Shannon proved in the channel coding theorem that this channel capacity equals the mutual information of the channel maximized over all possible input distributions [Shannon, 2001, Cover and Thomas, 2006]:

$$C = \max_{p(x)} \mathcal{I}(X; Y),$$