

## Principles of Embedded Networked Systems Design

Embedded network systems (ENS) provide a set of technologies that can link the physical world to large scale networks in applications such as monitoring of borders, infrastructure, health, the environment, automated production, supply chains, homes, and places of business. This book details the fundamentals for this interdisciplinary and fast-moving field. The book begins with mathematical foundations and the relevant background topics in signal propagation, sensors, detection and estimation theory, and communications. Key component technologies in ENS are discussed: synchronization and position localization, energy and data management, actuation, and node architecture. Ethical, legal, and social implications are addressed. The final chapter summarizes some of the lessons learned in producing multiple ENS generations. A focus on fundamental principles together with extensive examples and problem sets make this text ideal for use in senior design and graduate courses in electrical engineering and computer science. It will also appeal to engineers involved in the design of ENS.

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Cambridge University Press  
0521840120 - Principles of Embedded Networked Systems Design  
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**Gregory J. Pottie and William J. Kaiser**

University of California, Los Angeles



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[More information](#)

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CAMBRIDGE UNIVERSITY PRESS  
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo

CAMBRIDGE UNIVERSITY PRESS  
The Edinburgh Building, Cambridge CB2 2RU, UK

PUBLISHED IN THE UNITED STATES OF AMERICA BY CAMBRIDGE UNIVERSITY PRESS, NEW YORK  
[www.cambridge.org](http://www.cambridge.org)  
Information on this title: [www.cambridge.org/9780521840120](http://www.cambridge.org/9780521840120)

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First published 2005

Printed in the United Kingdom at the University Press, Cambridge

*A catalog record for this publication is available from the British Library*

*Library of Congress Cataloging in Publication data*

ISBN-13 978-0-521-84012-5 hardback  
ISBN-10 0-521-84012-0 hardback

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## Dedication

To Aldo, Cathy, Claire, and Laura for their patient love and support. To the dedicated and creative students and colleagues of the LWIM, AWAIRS, and CENS programs at UCLA and to the Sensoria Corporation team.

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# Preface

Embedded network systems (ENS) provide a set of technologies that can link the physical world to large scale networks for such purposes as monitoring of borders, infrastructure, health, the environment, automated production, supply chains, homes, and places of business. ENS nodes integrate the novel combination of signal processing, communication, sensing, and actuation technology. Their composition into large networks requires knowledge of networking and distributed software systems. Many excellent textbooks exist that treat these topics separately, and there are corresponding undergraduate and graduate courses. However, these provide both too much information on some topics and not enough on others for a course specifically devoted to ENS. The purpose of this book is to provide support for senior design courses and introductory graduate courses in ENS without the requirement for students to have expertise in all of these areas. As such it can also serve as a resource for the practicing professional in this rapidly expanding area of research and enterprise. Note what the book is *not*: a comprehensive and objective treatment of the latest developments in sensor networks. We do not presume to compete with the varied riches offered on the worldwide web by what is now a large and very creative group of researchers around the world. Therefore our focus is consciously on principles and methods which have proven useful to us in the course of designing multiple generations of ENS (research, commercial products, class projects), with digressions to what in our opinion are interesting topics for new investigations. We encourage our readers to go beyond our necessarily limited and subjective take on the facts, and delve deeper into this fascinating realm of research.

The book begins with an overview of ENS systems, and then discusses mathematical foundations, signal propagation, sensors, detection and estimation theory, and communications. Chapters 7 and 8 then discuss multiple access and networking issues, including information theoretic results that apply to sensor networks. Chapters 9–12 present other key component technologies in ENS: synchronization and position localization, energy management, data management, and actuation (both articulation and mobility). Chapters 13 and 14 discuss architectural principles for the design of nodes and networks of nodes that are to be remotely accessible, and means to ensure

the data are both trusted and secure. Chapter 15 discusses how to design experiments with ENS for some particular scientific purpose. Chapter 16 presents a number of questions for how ENS fit into our present and future societies. The final chapter summarizes a number of the lessons learned in producing multiple ENS generations. Appendix A consists of tables of the Gaussian  $Q$  function, while Appendix B provides an introduction to formal optimization techniques.

Clearly not all of these issues can be covered in a single quarter or semester, and in a design team not all of this expertise need reside in every individual. However, in total this is the set of topics that must be mastered in order to design efficient systems. It is expected that students will have a stronger background in some areas than others, with the topics selected tailored to their particular expertise, and the specific design concerns in the course. The material in this book might be supplemented with the basic science of some particular application such as seismic monitoring, and a system designed for that purpose. Chapter 16, on ethics and social impact, differs considerably in style from the other chapters and could, for example, in conjunction with Chapter 1 serve as a unit in an ethics class or as a stand-alone one-unit seminar course.

In a field that is rapidly changing and which spans such a broad set of topics we have opted to focus more upon basic principles than particular algorithms or hardware. A web site with reference designs from a senior design course will be maintained to provide up-to-date examples of software and hardware. Other resources available to instructors include a solution manual which we hope to supplement with new problems suggested by our readers, and equations and figures in electronic form to assist in the creation of lecture notes.

# Acknowledgments

The authors gratefully acknowledge the research contributions of many students and colleagues who over the years have turned nebulous concepts regarding sensor networks into real systems, both at UCLA and Sensoria Corporation. Particular thanks for direct contributions to this book go to Dr. Hong Chen, Huiyu Luo, Dr. Ameesh Pandya, and Dr. Yung-Szu Tu for the creation of problem sets (and solutions). Professor Andreas Savvides provided the position location Cramer–Rao bound example in Chapter 9, while Dr. Ryan Mukai provided the linearized multilateration problem formulation and establishment of a reference coordinate system. Richard Pon, Jason Gordon, Ryan Speelman, and Dustin McIntire characterized the IEEE 802.11b, narrowband radio, and microprocessor systems described in Chapter 13. The authors would also like to thank Dr. Fredric Newberg for much advice over many years in ENS system engineering and for the energy storage system analysis in this book. The genesis of Chapter 16 was a transdisciplinary set of discussions at the UCLA Institute of Pervasive Computing, moderated by Professors Jerry Kang and Dana Cuff. We are also grateful to both the Defense Advanced Research Projects Agency and the National Science Foundation for their support of numerous research projects in sensor networks that have enabled both our own work and the creation of a vigorous research community. Discussions at the NSF Center for Embedded Networked Sensing, under the leadership of Professor Deborah Estrin, have been a constant source of inspiration. The patience of the editorial team at Cambridge University Press for our perpetually pushed-back deadlines is also appreciated. Finally, we also thank our respective spouses, Aldo Cos and Cathy Kaiser for their cheerful tolerance of our many weekend and evening hours spent at work.

# Abbreviations

A/D	analog to digital
A/F	air-to-fuel
ACID	atomicity, consistency, isolation, durability
AEP	asymptotic equipartition property
AES	advanced encryption standard
ALU	arithmetic logic unit
AOA	angle of arrival
AODV	ad hoc on-demand distance vector
API	application program interface
APS	active pixel sensor
AR	autoregressive
ARQ	automatic repeat request
ASIC	application-specific integrated circuit
AWGN	additive white Gaussian noise
BFSK	binary frequency shift keying
BPSK	binary phase shift keying
BSC	binary symmetric channel
CA	certificate authority
CCD	charge coupled device
CCK	complimentary code keying
cdf	cumulative distribution function
CDMA	code division multiple access
CMOS	complementary metal oxide semiconductor
CN	central node
CPU	central processing unit
CSMA	carrier sense multiple access
CSMA/CD	carrier sense multiple access collision detection
CW	continuous wave
D/A	digital to analog
DARPA	Defense Advanced Research Projects Agency

DBMS	database management system
DCA	dynamic channel allocation
DES	data encryption standard
DFE	decision feedback equalizer
DMT	discrete multitone modulation
DPCA	dynamic power and channel allocation
DPSK	differential phase shift keying
DSR	dynamic source routing
DS-SS	direct sequence spread spectrum
DVS	dynamic voltage scaling
EDF	earliest deadline first
EGO	exhaust gas oxygen
EIRP	effective isotropic radiated power
ELSI	ethical, legal, and social implications
ENS	embedded network system
FCC	Federal Communications Commission
FDMA	frequency division multiple access
FEC	forward error correction
FET	field effect transistor
FFT	fast Fourier transform
FH-SS	frequency-hopped spread spectrum
FIR	finite impulse response
FOM	figure of merit
FPGA	field programmable array
FSK	frequency shift keying
ftp	file transfer protocol
FUSD	framework for user space device
GAF	geographic adaptive fidelity
GPIO	general purpose input/output
GPS	global positioning system
HAL	hardware abstraction layer
HD	Hamming distance
I/O	input/output
IDE	integrated drive electronics
IFFT	inverse fast Fourier transform
IP	internet protocol.
ISA	instruction set architecture
ISI	intersymbol interference
ISR	interrupt service routine
JTAG	Joint Test Action Group
JVM	java virtual machine
LAN	local area network
LEQ	linear equalizer
LIA	least interference algorithm
LMS	least mean square

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LNA	low-noise amplifiers
LP	linear programming
LRT	likelihood ratio test
LWIM	low-power wireless integrated microsensors
MAC	medium access control
MANET	mobile ad hoc networks
MAP	maximum a posteriori
MEMS	microelectromechanical system
MIMO	multiple-input multiple-output
ML	maximum likelihood
MLSE	maximum likelihood sequence estimation
MMSE	minimum mean square error
MMU	memory management unit
MOSFET	metal oxide semiconductor field effect transistor
MR	maximal ratio
MSE	mean square error
MUD	multiuser detection
MWE	multiwinner election
NACK	negative acknowledgement
NES	noise equivalent signal
NIMS	networked info-mechanical system
NLOS	non-line-of-sight
NP	Neyman-Pearson
NTP	network time protocol
OFDM	orthogonal frequency division multiplexing
OOK	on-off keying
PAM	pulse amplitude modulation
PAR	peak-to-average ratio
PCI	peripheral component interconnect
PCMCIA	Personal Computer Memory Card International Association
PDA	personal digital assistant
pdf	probability density function
PLL	phase lock loop
PN	pseudo-noise
psd	power spectral density
PSK	phase shift keying
PWM	pulse-width-modulated
PZT	pan/zoom/tilt
QAM	quadrature amplitude modulation
RAM	random access memory
RBS	reference broadcast system
RERR	route error
RF	radio frequency
RFID	radio frequency identification
ROM	read-only memory



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RREP	route reply
RREQ	route request
RS	Reed-Solomon
RSA	Rivest, Shamir, and Adleman
RV	random variable
SDMA	space division multiple access
SIR	signal-to-interference ratio
SISO	single-input single-output
SMACS	self-organizing medium access control for sensor networks
SNR	signal-to-noise ratio
SQL	structured query language
SRAM	static random access memory
SSH	secret shell
SSL	secure socket layer
SSS	strict-sense stationary
STEM	system topology and energy management
TCP	transport control protocol
TDMA	time division multiple access
TDOA	time difference of arrival
TH	Tomlinson-Harashima
TH-SS	time-hopped spread spectrum
TNEA	thermal noise equivalent acceleration
TNERR	thermal noise equivalent rotation ratio
TOA	time of arrival
UART	universal asynchronous receiver/transmitter
UDP	universal data protocol
USB	universal serial bus
UTC	coordinated universal time
UWB	ultra-wide-band
VCC	voltage-controlled clock
VCO	voltage-controlled oscillator
VOR	VHF omni-directional ranging
WSS	wide-sense stationary
ZF	zero-forcing