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Wireless Networks

FROM THE PHYSICAL LAYER TO
COMMUNICATION, COMPUTING,
SENSING AND CONTROL



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Wireless Networks

From the Physical Layer
to Communication, Computing,
Sensing, and Control

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Foreword

As president and CEO of the Italian industry holding FINMECCANICA, I am elated to introduce this book on wireless communication, which collects the edited lectures of a summer school sponsored by FINMECCANICA in the beautiful frame of the Capri island, Italy, in the fall of 2004. The book chapters are authored by prestigious names in the realm of the pertinent scientific arena.

As testified by its title, the book is characterized by an integral vision of wireless communication, from the physical layer to communication, computing, sensing, and control. I believe that this is the modern, right approach to present this material for the benefit of all the readers, spanning the academic world to the industrial environment. Information transfer is a key element in the structure of our society. The next step is its full integration with remote sensing, data access, real-time processing, and up to the final stage of far-away physical actions implementation.

The modern science was born with the experiments performed and the mathematical models developed by Galileo and Newton. The physical science emerged as a very important component of our society. Physicists were developing theories and models of natural phenomena, and a new segment of the civil society, the engineers, made use of above results and accomplishments to construct machineries, build up products, and provide services, thus usually rendering people's life more productive, rich, and enjoyable. But in the middle of the last century a novel and unique happening took place: engineers and not physicists created a novel branch of scientific knowledge, the communications discipline, and subsequently exploited its practical implementation. The first accomplishments were made by Shannon in the United States and Kotelnikov in Russia, creating the Information Theory and developing its implications and measurements concepts. Then, a full array of hardware components and software codes were developed and installed to synthesize wired and wireless

communication networks, vessels of the information blood of our society. As an electronic engineer myself and president and CEO of FINMECCANICA, with its over 8,000 engineers and 10,000 technicians, we are all very proud of all this.

We are now at the step of a further quantum leap: the integration of communication with computer processing, sensors data, and far-away actions. This is the academic and industrial answer to the new impelling demands raised by conventional traffic jams, homeland security, and life quality: it is the Global Village dream made true.

The book I am presenting is organized in this spirit, moving a small but significant step along this modern vision of wireless communication.

Dr. Ing. Piero Guarguaglini
FINMECCANICA President and CEO

Preface

This book collects the lectures held on the beautiful island of Capri during the fall of 2004. A great advantage of books resulting from short schools or specialized symposia is that they present the latest information on the subject, usually in a very readable form. At the same time, these books may lack an exhaustive full treatment of the matter, and some duplication of the material presented in different chapters may be expected. It is the responsibility of the editors to minimize these shortcomings without possibly impairing the freshness of the presentation by changing a collection of lectures into a formal textbook. This is what we tried to accomplish with a careful revision of all chapters provided by the school lecturers, but without enforcing our style, viewpoint, and perspective upon their writings.

The book consists of seven chapters that, except the first one, are derived from the school lectures. Each one of these chapters coincides with the revised (by each author) version of the school notes with a final (soft) touch by the editors. The chapters derived from the lecturers are presented first.

Chapter 2 outlines what makes radio communications distinct from wired communications at the physical layer and highlights current trends in radio design. An overview of radio wave propagation and its impact on communication system design is given. The issues of fading and path loss and their impact on the range and reliability of communications are presented. Modulation and coding techniques commonly used in wireless communications are considered. The importance of diversity in achieving reliable data communications is stressed, and an overview of techniques used to achieve diversity is provided. Radio architectures used in modern communication systems are discussed.

Chapter 3 is devoted to the receiving element of the wireless channel: the handheld, wearable, and implantable antennas used in personal communication technology. This is a very important issue,

because their design should account for the electromagnetic interaction between the antenna and the human body, a key factor to be considered. A full array of results on this subject is presented: popular antenna designs (such as monopole, inverted F, reconfigurable patches, etc.), numerical techniques for antenna performance evaluation, electromagnetic exposure of people to handheld receiving devices, Specific Absorption Rate (SAR) for adults and children, etc. The chapter is characterized by a large amount of first-hand experimental results on innovative realizations and related tests performed at the UCLA Electrical Engineering Department.

Chapter 4 consists of an overview of the models of the wireless channel, including both numerical procedures and analytical results. The former can be used for the analysis of a specific built-up scenario and can lead to the generation of electromagnetic solvers, where ray tracing techniques, including reflected, diffracted, and creeping rays, are implemented. Solvers complexity is discussed, highlighting their advantages and limitations; details and results related to a particular solver are presented also. On the analytical side, the latest statistical techniques are introduced, ranging from random walk theory to innovative percolation models of the urban scenario. Applications to the evaluation of expected values of electromagnetic quantities of interest (as, for instance, the path loss) are presented, with analytical, numerical, and experimental results.

Chapter 5 presents an overview of ad hoc wireless networks, the kind of wireless technology that enables untethered, wireless networking in environments where there is no established wired or cellular infrastructure (e.g., battlefield, disaster recovery, homeland defence) or where it is not cost effective to use an existing infrastructure (e.g., personal networking, collaborative computing). All their characteristics, such as mobility, multihopping, self-organization, energy conservation, scalability, security, etc., are introduced. The challenges of the network layer — routing and multicast — are discussed, providing all the necessary details with reference to the areas of sensor networks, automated battlefield, and collaborative computing. The MINUTE-MAN (Multimedia Intelligent Network of UnatTended Mobile AgeNts) project, developed at UCLA, is presented as a case study, including simulation experiments and their discussion.

Chapter 6 deals with acquisition, processing, compression, communication, and reconstruction of real-world signals, like sound and video, in a distributed environment. A unified treatment of data representation, routing, and node placements in a sensor network is

presented, which sets in the right perspective the optimization of various metrics of interest, particularly energy efficiency and accuracy of data reconstruction. Challenging questions, including fundamental, algorithmic, and practical issues, are addressed, with reference to lossless and lossy coding, optimal node placement problem, data gathering, and total distortion assessment. A relevant feature of this chapter is the treatment of the tight connection between data structure and transport mechanism, considered as the central challenge in the design of operational sensor networks.

Chapter 7 describes the latest results in wireless networks, providing an overview on the possible future scenario. Scaling laws are discussed, both with respect to current technological efforts and to the ultimate information-theoretical capability. Optimal architectures for information transport, protocol design, power control, medium access control, and routing are addressed. Nodes that can sense, compute, and wirelessly communicate are examined in detail. For such networks the problems of communication, sensing, and data fusion are inseparable; this next phase of the information technology revolution — the convergence of control with communication and computing — is examined. Even the implementation of far-away actions is briefly touched. The architectures of these widely integrated network systems and the prerequisites for their proliferation are addressed.

Examination of the content of the book shows that all the trajectories of wireless communication (as anticipated in the book title) are included. Coding and protocols; electromagnetic channel models; communication and sensors networks, as well as their integration; critical design issues to minimize the exposure to the electromagnetic fields while using the receiving devices; recent applications to homeland security and disaster recovery and mitigation; and the present and the possible future of this research area are all somewhere available in these chapters, linked by a logical progression. This unified treatment is unique, introducing the reader to this intriguing and fascinating world and providing a valuable scenario with all of its facets. Accordingly, the scientific and technical issues are all well covered. It seemed appropriate to also add an introductory chapter (whose material was not presented during the Capri school) outlining the impact of these emerging technologies on our life, and their shaping and addressing by our society needs. This short introduction, presented in Chapter 1, clearly does not pretend to be complete and rigorous. It only tries to set all the material of the subsequent chapters in the frame

of its applications context, presenting the players of this complicated scenario and anticipating the possible future developments.

Some few considerations about the potential audience of this book may be appropriate. It is easily anticipated that the book may be useful to the large variety of scientists and technicians working in the area of wireless communication. Each category will find updated information about its specific application area, with the additional advantage of being also exposed to its connections with the nearby areas. This was the spirit of the school, and it has been saved in the book, also.

It might be concluded that the book audience is limited to professionals in the specific covered field, but this is not completely true. As discussed at the end of Chapter 1, the new, cross layer, interdisciplinary design paradigm in the communication networks area requires not only in-depth expertise in one specific layer, but also a well rounded scientific background that integrates, among others, all the disciplines touched in the book. It is responsibility of the academia to realize a program that can educate and form the *telecommunications engineers* of the future. It can be anticipated that an array of new *wide band* courses should be designed and implemented. The book we are presenting is certainly not a textbook by itself, but it might be initially integrated by notes for such a task, leading eventually to a more formal textbook realization. We conclude that an additional non-negligible audience is expected in the universities and among professors and graduate students.

The presentation of a book is usually concluded with appropriate acknowledgments to all those who helped its realization. But our acknowledgments are toward colleagues that provided much more than significant help, because they essentially wrote the book. Accordingly, we are deeply indebted to Professors Michael Fitz, Mario Gerla, Yahja Rahmat-Samii of UCLA, P. R. Kumar of UIUC, Massimo Franceschetti of UCSD, Martin Vetterli of EPFL and UC Berkeley, and Daniele Riccio of University Federico II Napoli: they transformed their lectures into chapters, some of them with the help of their collaborators Cong Shen, Michael Samuel, Zhan Li of UCLA, and Razvan Cristescu of Caltech. Our appreciation is also for the Elsevier staff, in particular, for the Assistant Editor, Rachel Roumeliotis, and the Project Manager, Brandy Lilly, who continuously encouraged and pushed us to complete our job. We also thank FINMECCANICA, who sponsored the school, and all the participants, for their comments and suggestions.

We can certainly state that this book has been a cooperative job. It is very likely that everyone should thank each other. Our personal view is not only that cooperation is the right way to proceed, but it should even be extended, especially in these research areas that exhibit such an important connection with the organization of our society. As noted in Chapter 1, there is increasing attention of national and international authorities to assure a friendly and safe environment to the social community, which implies early time knowledge of emergence situations, follow up in real-time of the evolving scenario, and final evaluation and intervention by using a decision making system, usually remotely located. These requirements may be fulfilled by the appropriate use of information and communication technologies, along the integrated view presented in this book. It is very desirable that a permanent exchange of information, about technological offerings and expected requirements, occur between the scientific community and all those public authorities whose officers are aimed at assuring a safer and most secure environment to all of us. We will say with Keats that this is

*A hope
beyond the shadow
of a dream.*

[From "Endymion" by John Keats]

And to all these officers this book is dedicated.

The Editors

About the Authors

The short biographies are organised according to the Authors appearing from Chapter 1 to 7

Chapter 1

Giorgio Franceschetti was born and educated in Italy. Winner of a nationwide competition, he was appointed professor of Electromagnetic Theory at the University Federico II of Napoli, Italy in 1969, position that he holds since then. He has been Fulbright Scholar and Research Associate at Caltech, Visiting Professor at the University of Illinois, at UCLA, at the Somali University (Somalia) and at the University of Santiago de Compostela (Spain). In addition to his Chair at the University Federico II in Italy, he is currently Adjunct Professor at UCLA, Distinguished Visiting Scientist at JPL and Lecturer at the Top-Tech Master of University of Delft, The Netherlands, in Satellite Navigation. Author of over 150 (refereed) papers on Journals of recognized standard and nine books, and recipient of several awards, he is active in research on Electromagnetic Theory and Applications, Signal Processing, Synthetic Aperture Radar Imaging and Electromagnetic Propagation in complex media. He is Life Fellow of IEEE and Member of the Electromagnetic Academy. He recently received the gold medal from the President of the Italian Republic for his achievements in culture and science.

Sabatino Stornelli was born in Avezzano, Italy, in 1957. He graduated in Electrical Engineering at the University of L'Aquila, Italy, in 1982, with subsequent post-graduate additional studies at the Universities La Sapienza of Roma (Italy) and of Portland, Oregon (USA). After some industrial experience in Italy, he joined the European Space Agency (ESA) from 1987 to 1991, with R&D responsibilities in the Department of Information Technology. Coming back to Italy, he resumed his industrial activity, from 1991 to 1995 in Dataspazio and from 1995 to 2003 in Telespazio, operating in the area of Space Systems and Earth

Observation: his responsibilities steadily increased, reaching the level of CTO in 2000 and then General Director in 2001. Finally, in the year 2004 he was appointed CEO of Seicos, and in 2006 of Selex-SeMa, both of them Finmeccanica Companies operating in the area of Telecommunication Services, positions that he holds since then. In addition to this intense industrial activity, he has been Contract Professor at the Department of Aerospace Engineering of the University La Sapienza of Roma, Italy, in the years 1999–2000; he presented over 20 papers at International Symposia in the area of Satellite Navigation, Spacecraft Control and use of satellites for Environment Risks Management. In 1996 he got an Award from the Ukraine Academy for his activity in the area of Definition, Design and Management of Space Missions.

Chapter 2 [Course Lecturer: Prof. Michael Fitz]

Michael Fitz was born in Akron, Ohio (USA) in 1960. He obtained his Bachelor of Engineering Degree in Electrical Engineering from University of Dayton in 1983, and his M.S. and Ph.D. degrees in Communication Science from the University of Southern California, in 1984 and 1989, respectively. Dr. Fitz has been a professor at Purdue University, the Ohio State University, and the University of California Los Angeles (UCLA), and has held numerous positions in the private sector where he is currently employed at Northrop Grumman in Redondo Beach, CA. He was a recipient of the IEEE Communications Society Leonard G. Abraham Prize Paper Award. He is a co-author of the soon to be published book “A First Course in Communication Theory”.

Cong Shen was born in China on July 1980. He obtained his B.E. and M.S. degrees, in 2002 and 2004 respectively, from the Department of Electronic Engineering, Tsinghua University, China. After that he joined Wireless and Networking Group at Microsoft Research Asia (MSRA) as a full-time visiting student in 2004. Currently he is pursuing his Ph.D. at Electrical Engineering Department, UCLA. His research interests include information theory, wireless communications and networking. He is IEEE Student Member.

Michael Samuel was born in Cairo, Egypt in 1976. He obtained his B.Sc. degree in Electrical Engineering from Ain Shams University, Cairo, in 1999 and his M.Sc. degree in Communication Technology from the University of Ulm, in 2003. He is currently pursuing his Ph.D. degree at the Electrical Engineering Department, UCLA.

Chapter 3 [Course Lecturer: Prof. Yahya Rahmat-Samii]

Yahya Rahmat-Samii was born in Tehran, Iran. He obtained his B.S. Degree in Electrical Engineering from Tehran University and his M.S. and Ph.D. degrees from the University of Illinois, Champaign-Urbana. He is a distinguished professor and past chairman of the Electrical Engineering Department at the University of California, Los Angeles (UCLA). Before joining UCLA, he was a Senior Research Scientist at NASA Jet Propulsion Laboratory (JPL). He became a Fellow of IEEE in 1985, and was elected as the president of IEEE Antennas and Propagation Society (AP-S) in 1995. Rahmat-Samii has published over 650 journal and conference papers and over 20 books/book chapters in the areas of electromagnetics and antennas. He is the recipient of a large number of awards: two (1992 and 1995) Wheeler Awards for best application papers published in IEEE AP-S Transactions; the University of Illinois ECE Distinguished Alumni Award (1999); the IEEE Third Millennium Medal and the AMTA Distinguished Achievement Award (both in the year 2000); the Technical Excellence Award from JPL (2002); and finally he is the winner of the 2005 International Union of Radio Science (URSI) Booker Gold Medal presented at the URSI General Assembly, New Delhi, India. In 2001, he received an Honorary Doctorate in Physics from one of the oldest Universities in Europe, the University of Santiago de Compostela, Spain. In 2001, he was elected as the Foreign Member of the Royal Academy of Belgium for Science and the Arts. Professor Rahmat-Samii is the designer of IEEE AP-S logo.

Zhan Li was born in Nanjing, China on April 27, 1974. He obtained his B. Sc. and M. Sc Degrees in Electrical Engineering (Radio Electronics) from Nanjing University of Science & Technology in 1995 and 1998, respectively. In March 2005, Zhan received his Ph. D Degree in Electrical Engineering from University of California, Los Angeles (UCLA). He joined the CDMA Research & Development Centre of Nokia Inc. in 2000, where he is currently a Sr. Antenna Design Engineer. His recent research area focuses on the multiple-antenna solution for the handset. He has published 3 journal papers and presented several conference papers at Antenna Propagation Symposia since 2000.

Chapter 4 [Course Lecturers: Prof. Massimo Franceschetti and Prof. Daniele Riccio]

Massimo Franceschetti was born in Napoli, Italy, in 1972, and is currently is Assistant Professor in the Department of Electrical

and Computer Engineering of University of California at San Diego (UCSD). He received the Laurea degree, magna cum laude, in Computer Engineering from the University Federico II of Napoli, Italy, in 1997, and the M.S. and Ph.D. degrees in Electrical Engineering from the California Institute of Technology in 1999 and 2003, respectively. Before joining UCSD, he was a post-doctoral scholar at University of California at Berkeley for two years. At Caltech, his doctoral thesis was awarded the C.H. Wilts Prize for best thesis in Electrical Engineering, and the 2000 Walker von Brimer award for outstanding research initiative. Prof. Franceschetti also received (jointly with profs. J. Bruck and L. J. Shulman) in 2004 the S.A Schelkunoff award for the best paper published in IEEE AP-S Transactions, for his work on wave propagation and scattering based on random walk theory. He held visiting positions at the Vrije Universiteit Amsterdam in the Netherlands, the Ecole Polytechnique Federale de Lausanne in Switzerland, and the University of Trento in Italy. His research interests include random networks for communication, wave propagation in random media, and control over networks.

Daniele Riccio was born in Napoli, Italy in 1962. He graduated in Electronic Engineering at the University Federico II of Napoli, Italy, where he is now Professor of Electromagnetics and Remote Sensing. His scientific activity, in the fields of microwave Remote Sensing and radio wave propagation in complex environments, is documented by over 40 papers published on Journals of recognised standard and by 2 books.

Chapter 5 [Course Lecturer: Prof. Mario Gerla]

Mario Gerla received a graduate degree in engineering from the Politecnico di Milano in 1966, and the M.S. and PhD degrees from UCLA in 1970 and 1973. He became IEEE Fellow in 2002. After working for Network Analysis Corporation, New York, from 1973 to 1976, he joined the Faculty of the Computer Science Department at UCLA where he is now Professor. His research interests cover distributed computers, communication systems and wireless networks. He has designed and implemented various network protocols (channel access, clustering, routing and transport) under DARPA and NSF grants. Currently he is leading the ONR MINUTEMAN project at UCLA, with focus on robust, scalable network architectures for unmanned intelligent agents in defense and homeland security scenarios. He is also

conducting research on scalable TCP transport for the Next Generation Internet (see www.cs.ucla.edu/NLR for recent publications).

Chapter 6 [Course Lecturer: Prof. Martin Vetterli]

Martin Vetterli was born in Switzerland in 1957. He received his Engineering degree from ETH in Zurich, his MS from Stanford and his Ph.D. from EPFL in Lausanne. In 1986, he joined Columbia University in New York, first with the Center for Telecommunications Research and then with the Department of Electrical Engineering where he was an Associate Professor of Electrical Engineering. In 1993, he joined the University of California at Berkeley, where he was Full Professor until 1997. Since 1995, he is a Professor at EPFL, where he headed the Communication Systems Division (1996/1997) and heads the Audio-visual Communications Laboratory. From 2001 to 2004 he directed the National Competence Center in Research on mobile information and communication systems. He is also a Vice-President for International Affairs at EPFL since October 2004. He has held visiting positions at ETHZ (1990) and Stanford (1998). His research interests are in the areas of applied mathematics, signal processing and communications. He is the co-author of a textbook on “Wavelets and Sub-band Coding”, and of over 100 journal papers.

Razvan Cristescu was born in Ploiesti, Romania. He graduated with a PhD in 2004 from EPFL and, after one year as a postdoctoral scholar at Caltech, he is now a Senior R&D Engineer with Becton Dickinson, Sparks MD. He was recipient of the 2005 Chorafas prize for his PhD thesis at EPFL. His scientific activity, in the field of sensor networks, is testified by five papers published on journals of recognised standard.

Chapter 7 [Course Lecturer: Prof. P.R. Kumar]

P. R. Kumar was born in Nagpur, India on April 21, 1952. He obtained his B. Tech. Degree in Electrical Engineering (Electronics) from I. I. T. Madras in 1973, and his M. S. and D. Sc. Degrees in Systems Science and Mathematics from Washington University, St. Louis, in 1975 and 1977, respectively. He was a faculty member in the Department of Mathematics, University of Maryland, Baltimore County, from 1977 to 1984, and since 1985 he has been at the University of Illinois, Urbana-Champaign, where he is currently Franklin W. Woeltge Professor of Electrical and Computer Engineering, and Research Professor of the Coordinated Science Laboratory. He is an IEEE Fellow, was a recipient

of the Donald P. Eckman Award of the American Automatic Control Council, and is the 2006 recipient of the IEEE Field Award in Control Systems. He is a co-author of the book “Stochastic Systems,” with Pravin Varaiya.

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