New Directions in Wireless Communications Systems

From Mobile to 5G

Edited by Athanasios G. Kanatas
Konstantina S. Nikita • Panagiotis Mathiopoulos

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All the predictions available in the literature lead to the conclusion that beyond 2020, wireless communication systems will be able to support more than 1000 times the traffic volume served today by the current telecommunication systems. This extremely high traffic load is one of the major issues faced by the 5G designers, manufacturers, and researchers, alike. It appears that this challenge will be addressed by a combination of parallel techniques that will use more spectrum more flexibly, realize higher spectral efficiency, and densify cells. Therefore, novel techniques and paradigms should be developed to support such challenges.

In this context, ***New Directions in Wireless Communications Systems: From Mobile to 5G*** addresses diverse key-point issues of the next-generation wireless communication systems and attempts to identify promising solutions. The core of the book deals with the techniques and methods belonging to what is generally referred to as *radio access network*. The increased needs and the users' expectations from the next-generation systems have been based for long on enabling technologies provided by the physical layer. These technologies are mainly developed to combat signal degradations imposed by the wireless channel and to support increased user data rates and improved QoS.

New Directions in Wireless Communications Systems: From Mobile to 5G

- Provides an overview of the wave propagation and modeling of radio channels with characteristics that vary in time and space
- Compares various channel models, analyzes modeling techniques (stochastic, ray-tracing, etc.), and covers the application of the involved theory in optimizing cell planning
- Presents state-of-the art channel models, derived from the latest measurement campaigns, in various propagation scenarios (indoor, outdoor, etc.)
- Provides the fundamental concepts and basic theoretical tools for the qualitative analysis of fading channels
- Reviews the most popular modulation techniques that have become strong candidates for the future generations of wireless standards

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711 Third Avenue
New York, NY 10017
2 Park Square, Milton Park
Abingdon, Oxon OX14 4RN, UK

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Kanatas
Nikita
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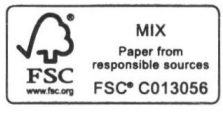

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New Directions in Wireless Communications Systems

From Mobile to 5G

Preface

We are experiencing the dawn of what is called the *digital age*. The Internet and digital technologies are transforming our world. Wireless communication systems constitute a basic component of the current and the future information society. The *fifth generation* of communication systems, or 5G, will be, in the years to come, the most critical building block of what is referred to as a *digital society*. It is expected that 5G will be a truly converged network environment, because not only mobile communications systems but also other wireless systems and wired networks will coexist and use the same infrastructure.

The vision ahead is that 5G will provide virtually ubiquitous, ultra-fastbroadband, *connectivity* not only to millions of individual users but also to billions of connected objects. Therefore, 5G systems should have the capabilities to (a) serve the data-hungry devices, for example, smartphones and tablets, providing rates of Gbps; (b) enable machine-to-machine (M2M) communications, for example, vehicle-to-vehicle (V2V) networks; (c) allow for interconnectivity of massive devices, for example, sensors and e-health equipment; and (d) support a wide range of applications and sectors. All these expectations set a wide variety of technical requirements for the design of 5G systems, including higher peak and user data rates, extremely low latency and response times, enhanced indoor and outdoor coverage, significantly increased number of devices, reaching the astronomical number of 100 billion, seamless mobility, security and privacy, increased battery lifetime, and improved quality of service (QoS) while maintaining low operational costs.

All the predictions available in the literature lead to the conclusion that beyond 2020, wireless communication systems will be able to support more than 1000 times the traffic volume served today by the current telecommunication systems. This extremely high traffic load is one of the major issues faced by the 5G designers, manufacturers, and researchers, alike. It appears that this challenge will be addressed by a combination of parallel techniques that will use more spectrum more flexibly, realize higher spectral efficiency, and densify cells. Therefore, novel techniques and paradigms should be developed to support such challenges.

In this context, this book addresses diverse key-point issues of the next-generation wireless communication systems and attempts to identify promising solutions. The core of the book deals with the techniques and methods belonging

to what is generally referred to as *radio access network*. The increased needs and the users' expectations from the next-generation systems have been based for long on enabling technologies provided by the physical layer. These technologies are mainly developed to combat signal degradations imposed by the wireless channel and to support increased user data rates and improved QoS.

Chapter 1 presents an overview of the wave propagation and modelling of radio channels with characteristics that vary in time and space. Then, the influence of multipath propagation on the signal-distorting characteristics of wireless channels and the resulting effects on digital communications are outlined. Both narrowband and wideband channel modeling is discussed with suggestions for assessing whether a wide-sense stationary (WSS) model is appropriate and for modeling channel processes with nonstationary characteristics and correlated scattering. Spatial channel characterization and MIMO channel models are reviewed and the measurement equipment and techniques are presented. Moreover, in Chapter 2, various channel models are compared, modeling techniques involved (stochastic, ray-tracing, etc.) are analyzed, and the applications of the involved theory in optimizing the cell planning procedures are demonstrated.

The millimeter-wave (mm-Wave) band has been foreseen for the development of 5G networks. A large amount of spectral space, from 28 to 95 GHz, is available to establish such systems providing increased data rates. Hence, the design issues of such networks necessitate the thorough knowledge of mm-Wave propagation characteristics. In Chapter 3, the state-of-the art channel models, derived from the latest measurement campaigns in various propagation scenarios (indoor, outdoor, etc.) are presented. In addition, models that describe the spatial–temporal variations of the mm-Wave channel are explained. Recent advances of MIMO and massive MIMO technology exploitation in mm-Wave propagation are also examined.

Chapter 4 presents the fundamental concepts and basic theoretical tools for the qualitative analysis of fading channels. This section helps the reader to understand the nature and types of fading, the basic characteristics of a wireless channel, and the impact of fading on signal transmission. Fading mitigation techniques are presented, and a complete classification of the existing transmit/receive diversity techniques that exploit the spatial, frequency, time, and the polarization domains, is also provided.

OFDM modulation and OFDM-based transmission schemes (e.g., OFDMA) have dominated the current modern wireless standards. However, despite OFDM's implementation simplicity, some key weaknesses such as the need for extended guard bands leading to reduced spectral efficiency, the increased peak-to-average power ratio, and its inherent sensitivity to frequency offset impairments have motivated in the research of alternative multicarrier or single-carrier modulation techniques based on filter banks. Therefore, Chapter 5 reviews the most important modulation and multicarrier schemes, including OFDM that have become strong candidates for the future generations of wireless standards.

The 5G radio access will be built on both new radio access technologies (RATs) and the evolved existing wireless technologies (LTE, HSPA, GSM, and WiFi). Chapter 6 provides an overview of radio network planning techniques from 2G to 4G. Then it describes the energy-efficient *green* radio network planning concept for heterogeneous 4G wireless networks and presents a cellular layout adaptation method.

The incorporation of MIMO transmission in the modern wireless standards has provided a significant improvement in the achieved spectral efficiency and system capacity. As technology moves toward 5G, the concept of MIMO has been evolved with the definition of complex centralized schemes, such as massive MIMO, or decentralized schemes, that is, network MIMO and coordinated multipoint transmission. Moreover, alternative advanced MIMO schemes reducing the number of required RF chains, enabling full duplex communications, and allowing the use of compact antennas have been considered. Chapter 7 reviews the most important trends and challenges in MIMO transmission with emphasis on their application to 5G systems.

Alternative enabling technologies are also presented. As an example, Chapter 8 introduces the load-controlled parasitic antenna arrays (LC-PAA) that resemble the operation of conventional antenna arrays with many elements, thus boosting the performance of multiantenna wireless communication systems, whereas at the same time providing cost and energy consumption savings and size reduction. Therefore, a novel method is presented that enables one to perform arbitrary channel-dependent precoding with LC-PAAs. The possible application of this technique in point-to-point MIMO, multiuser MIMO (MU-MIMO), coordinated MIMO, and massive MIMO setups is investigated. The design and implementation of various types of LC-PAAs for these frequency bands are also shown.

Spatial modulation (SM) has been recently proposed as a promising transmission concept that reduces the complexity and the cost of multiple-antenna schemes. At the same time, it guarantees high data rates, improved system performance, and energy efficiency. Working principles of SM are presented in Chapter 9 and the advantages and disadvantages of SM-MIMO as compared to the state-of-the-art MIMO communications are also discussed. Various transmission techniques for SM-MIMO, namely space shift keying (SSK), generalized space shift keying (GSSK) and generalized spatial modulation (GSM) are also further discussed. An analytical framework for the performance evaluation of SM-MIMO over fading channels in terms of the average bit error probability (ABEP) is also presented. Some MIMO transmission schemes closely related to the SM-MIMO paradigm, that is, single RF MIMO schemes, the incremental MIMO, and the antenna subset modulation (ASM) schemes, are briefly discussed. Moreover, several applications of SM-MIMO for future 5G wireless communications are presented, including MIMO implementations that exploit the massive MIMO paradigm as well as the combination of both orthogonal frequency division multiplexing (OFDM) and single carrier with SM-MIMO.

Device-to-device (D2D) communication is recognized as one of the technology components of the evolving 5G architecture. The reuse of cellular resources by D2D links that are located randomly inside a macro-cell imposes a cochannel interference to the base station (BS), cellular users and to other D2D receivers. Several aspects of D2D communications are investigated in Chapter 10, such as interference statistics of interferers scattered according to a homogeneous Poisson point process, D2D neighbor discovery based on signal-to-interference-and-noise ratio association metric, D2D link performance in the presence of interference and power control imposed by the BS, and the impact of mobility on the D2D link performance. In addition, a V2V use case is considered and the performance of a multiuser cooperative V2V communication system is studied.

Next, Chapter 11 addresses the virtualization of wireless access in order to provide the required capacity to a set of virtual base stations (VBSs) with diverse requirements, instantiated in a given geographical area. A network architecture is presented, based on a generic network virtualization environment, in which both physical and virtual perspectives are considered and the main stakeholders are taken into account. A new tier of radio resource management (RRM) is proposed for inter-VNets (virtual networks) RRM aiming at transposing the cooperative set of functionalities to the virtualization environment.

Cooperative techniques have significantly contributed toward improving the capacity of the 4G networks and are considered as a basic element of the imminent 5G networks. This topic is addressed in Chapter 12 of this book. Among cooperative techniques, cooperative relaying (CR) has received significant attention from researchers due to the gains that it offers to the network. The techniques that have received a large amount of contributions are the opportunistic relay selection (ORS) and successive relaying (SuR) and several policies, such as successive opportunistic relaying (SOR) with full duplex (FD) operation and SOR for networks with buffer-aided (BA) relays that offer additional degrees of freedom in inter-relay interference (IRI) mitigation. In addition, an overview of interference mitigation techniques designed for relay networks is provided.

Cognitive radio networks (CRNs) have been proposed as a promising solution to cope with the spectral scarcity, and this is the main topic of Chapter 13. In addition, as the technology of CRN can help to unlock the full potential of 5G wireless systems, the 5G key enablers are described and finally the role of CRN in 5G networks is also highlighted. Furthermore, several formulations of different CRN's resource allocation problems are presented based on various mathematical approaches such as optimization techniques, game theory, matching theory, multi-criteria decision-making theory, and machine learning. The basic concepts of each approach are described and an extensive list of scientific works is also presented. Finally, various future research avenues for the application of cognitive systems to 5G and the investigation of novel flexible algorithms in radio resource management are also discussed.

The last chapter (Chapter 14) focuses on transformational wireless technologies for health care, discussing their potential and the challenges that rose. As it is well known, the significant advances in wireless communications, sensing technologies, and sensor data analytics are opening new opportunities in medicine, and are promising to address the unsustainability of current health care provision models. Notably, health care challenges, including rising health care costs, aging populations, and emerging disease threats rank among the most serious concerns in the world. Wireless technology can empower both patients and medical providers by providing round-the-clock health status information. Examples include wireless on-body (wearable, epidermal) and in-body (implantable, ingestible) medical devices that may be used as sensors, actuators, and/or drug delivery devices. Remote diagnosis, vital parameter control, elderly monitoring, and chronic disease management are just some of the examples of applications of wireless technologies. Exploitation of wireless technologies and sensor data analytics in health care can lead to healthier citizens, reduced hospital stays, and lower costs.

This book is dedicated to Philip Constantinou, an inspiring professor, a valuable colleague, and a loyal friend. He was an exceptional professor who was always there for students, who could understand your thoughts and concerns, who was the inspiration, and who gave confidence to the team. A testimony to this was the overwhelming response we received from many colleagues who wanted to contribute to this book because they wanted to join us in celebrating his research and educational achievements in the general field of wireless communications for the past 25 years.

Philip was a kind human being, a generous and a welcoming person open to the community, showing great concern and affection for people with special needs. Before joining the National Technical University of Athens, Athens, Greece, he and his family have lived for many years in Canada, where he was granted the Master of Applied Science by University of Ottawa and started his great telecom career in Telesat in Ottawa, Canada. Then he worked for several years for the Government of Canada in the Department of Communications, while at the same time pursuing his PhD degree at the Carleton University, Ottawa, Canada. Being an international man, he believed in openness, valued collaboration, and always tried to impart the importance of communicating engineering novelty to his students. He was always supportive to the junior communications engineers' ideas and encouraged them to act on their own initiative following their dream. Philip was a workaholic lab enthusiast who loved to deliver working systems. Although he was a zealous and motivated leader, he had a methodic approach regularly reminding to his colleagues two of his favorite phrases: "One step at a time" and "I am always a practical man." His students and his colleagues, alike, owe him a great debt of gratitude for making us feel special, strong, and capable of doing things.

Athanasios (Thanasis) G. Kanatas
Konstantina (Nantia) S. Nikita
Panagiotis (Takis) Mathiopoulos

About the Editors

Athanasios (Thanasis) G. Kanatas is a professor at the Department of Digital Systems and dean of the School of Information and Communication Technologies at the University of Piraeus, Greece. He received his diploma in electrical engineering from the National Technical University of Athens (NTUA), Greece, in 1991, MSc degree in satellite communication engineering from the University of Surrey, Surrey, UK in 1992, and earned his PhD degree in mobile satellite communications from NTUA, Greece in February 1997. From 1993 to 1994 he was with National Documentation Center of the National Research Institute. In 1995, he joined SPACETEC Ltd. as technical project manager for VISA/EMEA VSAT Project in Greece. In 1996, he joined the Mobile Radiocommunications Laboratory as a research associate. From 1999 to 2002, he was with the Institute of Communication and Computer Systems responsible for the technical management of various research projects. In 2000, he became a member of the board of directors of OTESAT S.A. In 2002, he joined the University of Piraeus as an assistant professor. He has published more than 150 papers in international journals and international conference proceedings. He is the author of 6 books in the field of wireless and satellite communications. He has been the technical manager of several European and National R&D projects. His current research interests include the development of new digital techniques for wireless and satellite communications systems, channel characterization, simulation, and modeling for mobile, mobile satellite, and future wireless communication systems, antenna selection and RF preprocessing techniques, new transmission schemes for MIMO systems, V2V communications, and energy efficient techniques for wireless sensor networks.

He has been a senior member of IEEE since 2002. In 1999, he was elected chairman of the Communications Society of the Greek Section of IEEE. He has been a member of the TPC of more than 40 international IEEE conferences. He was a corecipient of two best paper awards for papers published in the International Conference on Advances in Satellite and Space Communications (SPACOMM), Athens, Greece, (2010) and Global Wireless Summit, Wireless VITAE, Atlantic City, United States, (2013).

Konstantina (Nantia) S. Nikita received her diploma in electrical engineering and earned her PhD degree from the National Technical University of Athens (NTUA), as well as MD degree from the Medical School, University of Athens. From 1990 to 1996, she worked as a researcher at the Institute of Communication and Computer Systems. In 1996, she joined the School of Electrical and Computer Engineering, NTUA, as an assistant professor, and since 2005, she serves as a professor at the same school. Moreover, she is an adjunct professor of Biomedical Engineering and Medicine, Keck School of Medicine and the Viterbi School of Engineering, University of Southern California. She has authored or coauthored 165 papers in refereed international journals, 41 chapters in books, and more than 300 papers in international conference proceedings. She is the editor of seven books in English and author of two books in Greek. She holds three patents. She has been the technical manager of several European and National R&D projects. She has been honorary chair/chair of the program/organizing committee of several international conferences, and has served as a keynote/invited speaker at international conferences, symposia, and workshops organized by NATO, WHO, ICNIRP, IEEE, URSI, and so on. She has been the advisor of 27 completed PhD theses, several of which have received various awards. Her current research interests include biomedical telemetry, biological effects and medical applications of radiofrequency electromagnetic fields, biomedical signal and image processing and analysis, simulation of physiological systems, and biomedical informatics. She is an associate editor of the IEEE Transactions on Biomedical Engineering, the IEEE Journal of Biomedical and Health Informatics, the *IEEE Transactions on Antennas and Propagation, the Wiley Bioelectromagnetics,* and *the Journal of Medical and Biological Engineering and Computing.* She has received various honors/awards, with the Bodossakis Foundation Academic Prize (2003) for exceptional achievements in "Theory and Applications of Information Technology in Medicine" being one of them.

She has been a member of the board of directors of the Atomic Energy Commission and of the Hellenic National Academic Recognition and Information Center, as well as a member of the Hellenic National Council of Research and Technology. She has also served as the deputy head of the School of Electrical and Computer Engineering of the NTUA. She is a member of the Hellenic National Ethics Committee, a founding fellow of the European Association of Medical and Biological Engineering and Science (EAMBES), a fellow of the American Institute of Medical and Biological Engineering (AIMBE), and a member of the Technical Chamber of Greece and of the Athens Medical Association. She is also a member of the BHI Technical Committee, the founding chair and ambassador of the IEEE–EMBS, Greece chapter and has served as the vice-chair of the IEEE Greece Section.

Panagiotis (Takis) Mathiopoulos is a professor of telecommunications at the Department of Informatics and Telecommunications, University of Athens, Greece. Prior to that, he was with the Institute for Space Applications and Remote Sensing (ISARS) of the National Observatory of Athens, first as its director (2001–2005)

and then as director of research (2006–2014). From 1989 to 2003, he was a faculty member in the Department of Electrical and Computer Engineering, the University of British Columbia (UBC), where he was a professor from 2000 to 2003. From 2008 to 2013, he was appointed as guest professor at the Southwest Jiaotong University, China. He has been also appointed by the Government of People's Republic of China as a senior foreign expert at the School of Information Engineering, Yangzhou University (2014–2016) and by Keio University as a visiting (Global) professor in the Department of Information and Computer Science (2015–2016 and 2017–2018) under the Top Global University Project of the Ministry of Education, Culture, Sports, Science, and Technology (MEXT), Government of Japan.

For the past 25 years, he has been conducting research mainly on the physical layer of digital communication systems for terrestrial and satellite applications, including digital communications over fading and interference environments. He coauthored a paper in GLOBECOM'89 establishing for the first time in the open technical literature the link between maximum likelihood sequence estimation (MLSE) and multiple (or multisymbol) differential detection for the AWGN and fading channels. He is also interested in channel characterization and measurements, modulation and coding techniques, synchronization, SIMO/MIMO, UWB, OFDM, software/cognitive radios, green communications, and 5G. In addition, since 2010, he has been actively involved in research activities in the fields of remote sensing, LiDAR systems, and photogrammetry. In these areas, he has coauthored more than 110 journal papers, mainly published in various IEEE and IET journals, 4 book chapters, and more than 120 conference papers.

Prof. Mathiopoulos has been or currently serves on the editorial board of several archival journals, including the *IET Communications,* and *the IEEE Transactions On Communications* (1993–2005). He has regularly acted as a consultant for various governmental and private organizations. Since 1993, he has served on a regular basis as a scientific advisor and a technical expert for the European Commission (EC). In addition, from 2001 to 2014, he has served as a Greek representative to high level committees in the European Commission (EC) and the European Space Agency (ESA). He has been a member of the TPC of more than 70 international IEEE conferences, as well as TPC vice-chair for the 2006-S IEEE VTC and 2008-F IEEE VTC as well as cochair of FITCE2011. He has delivered numerous invited presentations, including plenary and keynote lectures, and has taught many short courses all over the world. As a faculty member at the ECE of UBC, he was elected as ASI fellow and a Killam research fellow. He was a corecipient of two best paper awards for papers published in the *2nd International Symposium on Communication, Control, and Signal Processing* (2008) and *3rd International Conference on Advances in Satellite and Space Communications* (2011).