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History and Applications of UWB

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Ultrawide bandwidth (UWB) signals are commonly defined as signals that have a large relative bandwidth (bandwidth divided by the carrier frequency) or a large absolute bandwidth. The use of large transmission bandwidths offers a number benefits, including accurate ranging, robustness to propagation fading, superior obstacle penetration, covert operation, resistance to jamming, interference rejection, and coexistence with narrow bandwidth (NB) systems. On the other hand, generating, receiving, and processing UWB signals poses significant challenges that require new research in signal generation, transmission, propagation, processing, and system engineering.

This mathematical modeling method for wireless networks is designed to take into account propagation effects and interference from unwanted transmissions.

Due to its unique characteristics, several application areas have emerged for UWB, including:

i) short-range (< 10 m) communications with extremely high data rates (up to 500 Mbit/s)—for example, for wireless USB-like communications between computer components or wireless links among components of entertainment systems (DVD player and TV);

ii) sensor networks, where low-rate communications are combined with precise ranging and geolocation;

iii) radar systems, with the extremely high spatial resolution and obstacle penetration capabilities.

UWB radio is a field of research that is old and new at the same time. The first UWB signals were generated in experiments by Hertz in 1887, in which he generated sparks and radiated them via wide-band loaded dipoles. At that time, short, wide-band pulses were the easiest waveforms to generate. As time went on, the emphasis of communications systems shifted to narrow band carrier-based (tuned) systems, which were easier to multiplex with the technology available at that time. It was only in the 1990s that the improvements in digital signal processing, and the invention and investigation of time-hopping (TH) impulse radio, revived interest [1], [2]. This interest was greatly magnified by the decision of the U.S. frequency regulator, the

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Federal Communications Commission, to make the frequency band between 3.1–10.6 GHz available for unlicensed operation of UWB devices, subject to certain restrictions on the spectral emission mask. In subsequent years, many other countries, like Japan, Singapore, and the European Union, approved similar rules. Based on this new availability of spectrum, ad hoc standards were released and a number of products were developed and are now commercially available, or will become available soon. This commercial situation, as well as the wealth of academic and industrial research, makes it opportune to have a Special Issue that surveys the area of UWB communications and ranging, covering topics that span from communication theory to chip design to ranging and localization algorithms.

I. HOW TO GENERATE UWB SIGNALS

The basics of ultra-wide-band communications theory were a focal point of research in the 1990s and early 2000s, and have been well documented in the literature. Creating signals with very large bandwidth can be achieved in a number of different ways (see Fig. 1). Classical approaches are frequency-hopping (FH), TH, and direct-sequence (DS), in which the basic idea is to spread the signal spectrum through a proper combination of the original data stream with user-specific spreading codes. Another option is to allow conventional modulation schemes to work at extremely high (coded) data rate and, hence, very large bandwidth. To this purpose, modulation schemes robust to channel frequency selectivity, such as orthogonal frequency-division multiplexing (OFDM), are more appropriate, especially for short-range high-data-rate applications. Obviously, hybrid solutions, which combine the main features of different modulation schemes, are possible.

More specifically, in FH, different carrier frequencies are used at successive time slots according to a user-specific spreading code; narrow-band transmission occurs for a time T_{hop} on carrier frequency $f(t_1)$, then at frequency $f(t_2)$, and so on. The duration of T_{hop} can be chosen to be i) smaller than a symbol duration ("fast hopping"), so that each symbol is spread over several carrier frequencies, ii) larger than a symbol duration ("slow hopping"), so that several adjacent symbols are transmitted on the same carrier frequency, or iii) equal to the symbol duration. The bandwidth occupied by a frequency-hopped signal is determined by the range of the hopping frequencies, not by the data rate. A variation of frequency hopping is chirp signaling, where the carrier frequency changes continuously.

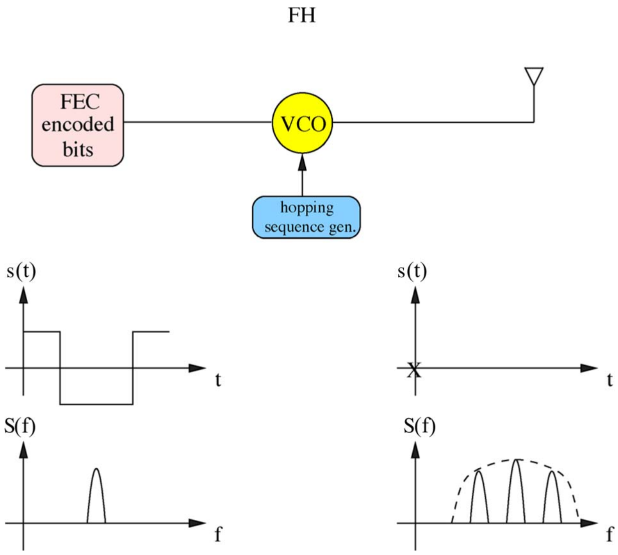

Fig. 1. *Principle of FH spreading. FEC: forward error correction. VCO: voltage-controlled oscillator. $s(t)$: signal in the time domain. $S(f)$: spectrum of the signal.*

DS signals can be generated by multiplying the original data stream with a high-rate *pseudorandom* sequence (spreading code), resulting in a signal with a spread spectrum, see Fig. 2. The bandwidth of the transmitted signal is determined by the rate of the spreading sequence, which is typically much higher than the data symbol rate. The spreading process can also be seen as a form of low-rate repetition coding. At the receiver, the original data symbols can be recovered by correlating the received signal with the same spreading code used at the transmitter (despreading). The adoption of spreading codes with properly designed characteristics in terms of auto- and cross-correlation allows DS transmission to be robust to interference, both NB and multiuser, and to multipath propagation.

TH impulse radio (TH-IR) can be thought of as dual of the FH technique. Here, in fact, each data symbol is associated to a sequence of very short duration pulses having their relative positions hopping in time according to a user-specific sequence. Due to the short pulse duration, the spectrum is spread. In principle, the generation of this "carrier-less" signal allows for low-complexity and low-power-consumption transmitter implementation. TH-IR also offers the possibility of low- complexity noncoherent receivers, see Fig. 3. TH-IR was the first proposed UWB scheme and has received most of the attention in the research community.

OFDM creates a wide-band signal from many narrow-band signals, whose spectra occupy different parts of the overall wide-band spectrum. Specifically, the original bit stream is split in several *parallel* low-data-rate streams, each of them modulating different parallel carriers (subcarriers). The spacing of the subcarriers is chosen in such a way that the signals

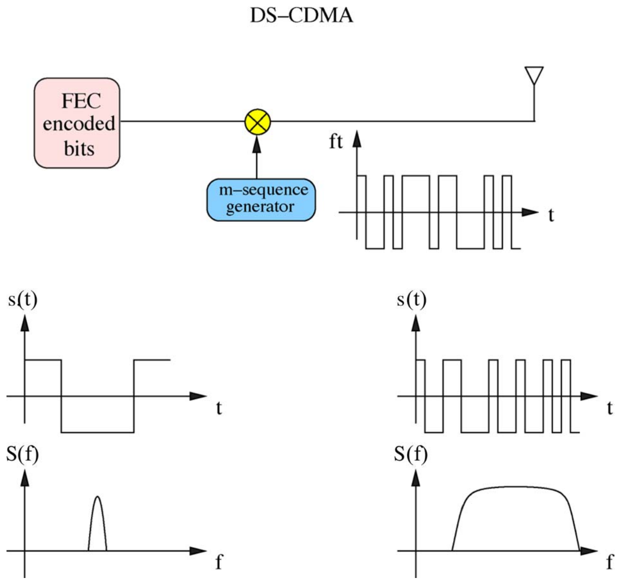

Fig. 2. ***Principle of DS code-division multiple-access spreading. $s(t)$: signal in the time domain. $S(f)$: spectrum of the signal.***

belonging to different subcarriers are orthogonal to each other even though their spectra overlap. This leads to a highly spectrally efficient modulation method. In practice, it is not necessary to generate the different subcarriers using a multitude of local oscillators and modulators, but rather can be implemented digitally by performing an inverse fast Fourier transform (IFFT). The addition of channel coding schemes enables the receiver to exploit a high coding gain and take advantage of channel frequency diversity, and leads to robust performance.

Irrespective of the specific modulation scheme adopted, on their way from the transmitter to the receiver, the UWB signal usually goes through a multipath channel, which leads to a delay dispersion. This multipath propagation is especially important for UWB signals due to the large bandwidth (for a detailed description of this effect, see the paper by Molisch in this issue). A UWB receiver can resolve (distinguish) multipath components that are approximately $1/B$ apart in the delay domain. Since B is very large, this implies that the number of multipath components, distinguishable by the receiver, could be very high. This has advantages with respect to the robustness of the receiver [3], [4] but also makes the construction of UWB receivers more difficult because the different multipath components have to be received and processed in some form. DS and TH-IR can exploit Rake receivers, which use separate correlators to receive the different multipath components. Alternatively to Rake receivers, transmitted reference (TR) signaling, in conjunction with autocorrelation receivers, has been proposed [5]–[7]. TR systems can exploit multipath diversity inherent in the environment without the need for channel estimation and stringent acquisition. OFDM receivers, on the other hand, inherently deal with the multipath propagation: by distributing the signal over a number of NB subcarriers, each subcarrier does not suffer from significant delay dispersion.

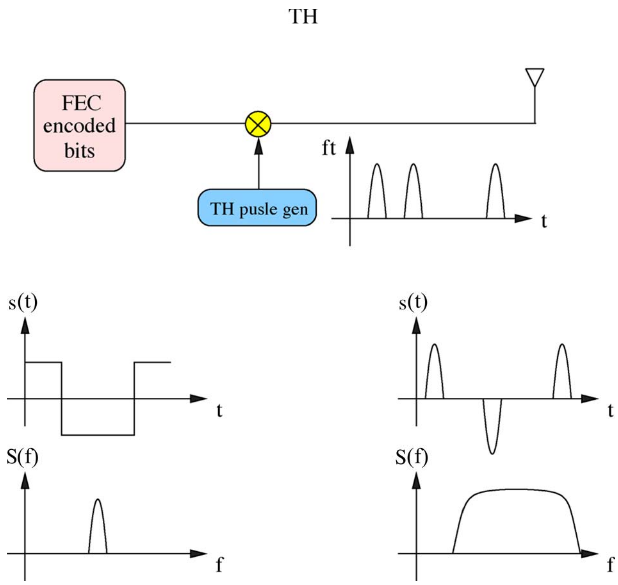

Fig. 3. ***Principle of TH impulse radio. $s(t)$: signal in the time domain. $S(f)$: spectrum of the signal.***

Recently, OFDM-based UWB technology has been adopted in the ECMA-368/9 (WiMedia Alliance) standard for short-range high-data-rate transmission [8], see Fig. 4. On the other hand, due to its low-complexity and low-consumption characteristics, the TH-IR modulation scheme has been chosen in the IEEE 802.15.4a standard, which addresses wireless personal area networks (WPANs) and wireless sensor networks (WSNs), low-data rate applications with ranging and localization capabilities (see the paper by Zhang *et al.* in this issue).

II. THE PAPERS IN THIS SPECIAL ISSUE

The papers in this Special Issue can be grouped into three parts: i) theory and implementation of transmission

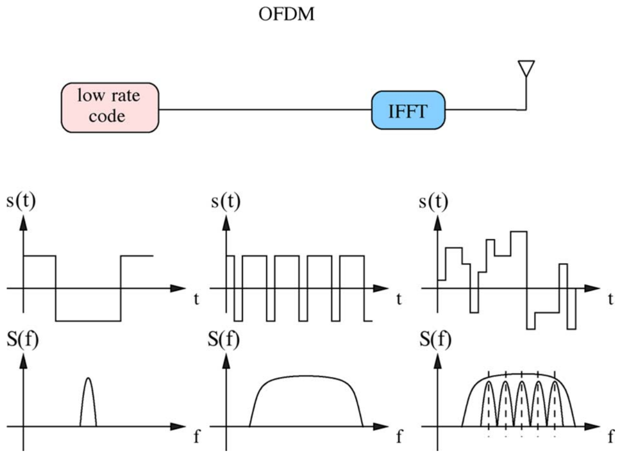

Fig. 4. ***Principle of OFDM. IFFT: inverse fast fourier transform. $s(t)$: signal in the time domain. $S(f)$: spectrum of the signal.***

technology; ii) channels, antennas, and hardware; and iii) geolocation and radar. The papers range from tutorial expositions to detailed descriptions of recent research work. In the spirit of the PROCEEDINGS OF THE IEEE, the choice of topics is intended to stimulate interest for UWB in a wide variety of research communities. We also mention that a number of introductory papers and monographs have been published in recent years [9]–[14].

A. Theory and Implementation of Transmission Technology

In a wireless network composed of many spatially scattered UWB nodes, it is important to characterize the accumulation of signals radiated by the various transmitters, which can undesirably affects receiver nodes in the network. The paper "A Mathematical Theory of Network Interference and Its Applications," by Win *et al.* introduces a unifying mathematical framework for the characterization of network interference in wireless systems. The utility of this framework is illustrated with applications: 1) interference in cognitive radio networks, 2) interference in wireless packet networks, 3) spectrum of the aggregate radio-frequency emission of wireless networks, and 4) interference between UWB and NB systems.

One key aspect of UWB systems is their coexistence with other systems. This is possible if the mutual interference has a small impact on their respective performances. The paper "Coexistence Between UWB and Narrow-Band Wireless Communication Systems" by Chiani *et al.* presents recent results on the interference and coexistence among UWB systems and other conventional NB systems. Both IR-based and OFDM-based UWB systems are considered, in wireless channels including thermal noise and multipath, for a finite number of interferers. With the aim of focusing on fundamental issues, the paper treats 1) the effect of NB interfering signals on UWB-IR receivers; 2) the effect of NB interfering signals on UWB-OFDM receivers employing forward error correcting (FEC) codes; 3) the effect of UWB-IR interfering signals on NB receivers; and 4) the effect of UWB-OFDM interfering signals on NB receivers. The paper further discusses where and when it is possible to approximate the interfering signals with simpler signals (e.g., tones, Gaussian processes, train of Dirac-delta impulses) to derive simple error probability expressions that provide useful insights for system design.

UWB systems located in the same coverage region will experience multiple-user interference (MUI), and the mitigation of such MUI is an important issue for the design of robust receivers. In "Designing Time-Hopping Ultrawide Bandwidth Receivers for Multiuser Interference Environments," Beaulieu and Young consider the unique characteristics of interference in time-hopping UWB systems and summarize recent work on the topic. Several statistical models for time-hopped UWB MUI are presented, motivating novel receiver designs for environments where MUI is significant. Several of these receivers have adaptive implementations that effectively cope with MUI, multipath fading, and additive white Gaussian noise, providing significantly lower error-rate floors in comparison to the conventional linear receiver.

While UWB by itself can already provide high data rates, further increases to 1 GBit/s and beyond may be achieved by employing multiple-input multiple-output (MIMO) techniques via the use additional antennas. This topic is explored in "An Overview of Ultra Wideband Systems with MIMO" by Kaiser and Zheng. It is shown that the special fading statistics and the frequency-dependent path loss make the capacity expressions of MIMO-UWB systems more involved than for the NB case. Instead of higher data rates, multiple antennas can be used to increase range through beamforming. The mechanisms for beamforming are different from the NB case, and conditions are given for the optimal beamformer. With this beamformer, the strength of the side lobe becomes independent of the ray incidence angle.

In recent years, there has been a great interest in WSNs as well as WPANs. These low-data-rate networks pose several design constraints in terms of cost, energy consumption, and stringent ranging accuracy to enable localization-based services. IEEE802.15.4a is an emerging standard that defines a UWB IR-based low-data-rate WSN/WPAN specification to provide robust communications and precise ranging between devices. The paper "UWB Systems for Wireless Sensor Networks" by Zhang *et al.* first discusses the various ways of designing UWB-based sensor networks and discusses the advantages and drawbacks of different spreading technologies and multiple-access methods in this context. The paper then gives a tutorial overview of the IEEE802.15.4a standard with particular attention to its adoption for WSNs. The main functionalities are described by outlining the innovative design criteria of the physical layer and precision two-way ranging schemes, with special treatment for security ranging.

B. Channels, Antennas, and Hardware

Many applications that UWB technologies are targeting require battery operated or even batteryless devices, and therefore energy-efficient implementation is critical for the successful penetration of the technology. The paper "Low-Power Impulse UWB Architectures and Circuits" by Chandrakasan *et al.* addresses many of the low power implementation challenges from both the system architecture to circuit-level design techniques. In particular, the paper presents two custom impulse UWB systems that are suitable for high- and low-data-rate applications, respectively. In the 100 Mb/s high-rate system, parallelism is applied to allow the use of energy-efficient architectures and aggressive voltage scaling. The low-rate system has an all-digital transmitter and a receiver with a low-voltage radio frequency and local oscillator-free analog circuits. The design also takes advantages of the low duty cycle nature of impulse radio to achieve energy saving.

In order to build systems that realize the potential of UWB, it is required to understand UWB propagation and the channel properties arising from this propagation. Obviously, the absolute performance of a given system depends on the channel—the path gain is one, but certainly not the only, example of a propagation effect that determines whether a system can perform satisfactorily. The paper "Ultra-Wide-Band Propagation Channels" by Molisch first discusses the multipath propagation and the distortions each multipath component suffers, stressing the differences with NB propagation. The paper also describes channel models, both deterministic and stochastic, and describes the typical model parameter values based on realistic channel measurements.

The paper "Ultra-Wide-Band Antennas" by Wiesbeck *et al.* introduces the basic principles of UWB radiation and discusses the influence of antennas on UWB transmission. Antennas are essential elements, especially in UWB systems. Not only beam width, gain, and side-lobes, but also their peak amplitude, width of pulses, ringing, and spatial correlation are of major interest. There are several generic ideas for the development of UWB antennas like traveling wave, frequency independence, multiple reonance, or electrically small configurations. In this issue, the basic principles are discussed and measurement results presented for the different UWB antenna types. For dedicated applications, the antennas have to be selected according to the required features.

C. Geolocation and Radar

UWB systems are inherently well suited for accurate ranging, and consequently high-precision geolocation, since the use of extremely large transmission bandwidths results in fine delay resolution. The paper "Position Estimation via Ultra-Wide-Band Signals" by Gecizi and Poor reviews the issue of geolocation. It starts by describing the various types of UWB signals, and the various ways of range estimation [signal strength, direction-of-arrival (DOA), time-of-arrival (TOA), and time-difference-of-arrival]. The authors then describe how to get position estimates from range estimates, and furthermore discuss the factors influencing the achievable accuracy, including noise, signal distortion on the channel, UWB signal design, and hardware implementation.

The paper "Ranging with Ultra-wide Bandwidth Signals in Multipath Environments" by Dardari *et al.* describes the challenges and performance limits in time-based ranging using UWB signals in a variety of environments. The paper first provides an overview of error sources in time-based ranging, including propagation, clock drift, and interference. It then goes on to quantify ranging performance limits via Cramer–Rao bounds and Ziv–Zakai bounds. Furthermore, the paper discusses optimal and practical TOA estimators and analyzes their performance in the presence of multipath, interference, and under bandwidth limitations. Results are presented for both ideal propagation environments and for realistic conditions using IEEE 802.15.4a channel models as well as measured data. Future research directions in this area are also discussed.

In the coming years, high-definition location-aware applications capable of operating in harsh propagation environments, where current technologies such as GPS typically fail, will play a fundamental role. Cooperation between nodes can be harnessed to improve the localization accuracy and reduce outages, especially in scenarios where a dedicated infrastructure is not available. In the paper "Cooperative Localization in Wireless Networks," Wymeersch *et al.* give an overview of cooperative localization approaches and apply them to UWB wireless networks. They present a powerful localization algorithm by mapping a graphical model for statistical inference onto the network topology, which results in a network factor graph, and network message passing. The performance of the resulting distributed algorithm is evaluated based on realistic UWB ranging models developed through an extensive measurement campaign with FCC-compliant UWB radios.

In "Ultra-Wide-Band Radar" by Jofre *et al.*, microwave tomography is discussed, which is an interesting research area not only for medical applications but also for material testing, localization, and so on. Microwaves have the advantage of good material penetration and of being less harmful than other technologies, e.g., x-ray, but they have the disadvantage of the by far longer wavelength. The longer wavelength requires sophisticated antenna configurations, usually multidimensional or scanning structures. This in turn requires dedicated imaging algorithms for focusing on the areas of interest. A general framework based on a UWB bifocusing operator with good tomographic imaging capabilities is presented in this issue. It is shown that the theoretical far-field resolution of half a wavelength (in the material) can be reached.

III. OUTLOOK

Presently, in many countries the research and development in UWB is widely supported by science foundations, governments, and industry. We hope that this Special Issue helps to disseminate the important advances that have been made in recent years and consequently stimulates new applications of this technology worldwide. By pointing out the wide range of required techniques and the breadth of applications, we also hope that interdisciplinary research will be further stimulated. ■

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ABOUT THE GUEST EDITORS

Moe Z. Win (Fellow, IEEE) received both the Ph.D. in Electrical Engineering and M.S. in Applied Mathematics as a Presidential Fellow at the University of Southern California (USC) in 1998. He received an M.S. in Electrical Engineering from USC in 1989, and a B.S. (*magna cum laude*) in Electrical Engineering from Texas A&M University in 1987.

Dr. Win is an Associate Professor at the Massachusetts Institute of Technology (MIT). Prior to joining MIT, he was at AT&T Research Laboratories for five years and at the Jet Propulsion Laboratory for seven years. His research encompasses developing fundamental theory, designing algorithms, and conducting experimentation for a broad range of real-world problems. His current research topics include location-aware networks, time-varying channels, multiple antenna systems, ultra-wide bandwidth systems, optical transmission systems, and space communications systems.

Professor Win is an IEEE Distinguished Lecturer and an elected Fellow of the IEEE, cited for "contributions to wideband wireless transmission." He was honored with the IEEE Eric E. Sumner Award (2006), an IEEE Technical Field Award for "pioneering contributions to ultra-wide band communications science and technology." Together with students and colleagues, his papers have received several awards including the IEEE Communications Society's Guglielmo Marconi Best Paper Award (2008) and the IEEE Antennas and Propagation Society's Sergei A. Schelkunoff Transactions Prize Paper Award (2003). His other recognitions include the Laurea Honoris Causa from the University of Ferrara, Italy (2008), the Technical Recognition Award of the IEEE ComSoc Radio Communications Committee (2008), Wireless Educator of the Year Award (2007), the Fulbright Foundation Senior Scholar Lecturing and Research Fellowship (2004), the U.S. Presidential Early Career Award for Scientists and Engineers (2004), the AIAA Young Aerospace Engineer of the Year (2004), and the Office of Naval Research Young Investigator Award (2003).

Professor Win has been actively involved in organizing and chairing a number of international conferences. He served as the Technical Program Chair for the IEEE Wireless Communications and Networking Conference in 2009, the IEEE Conference on Ultra Wideband in 2006, the IEEE Communication Theory Symposia of ICC-2004 and Globecom-2000, and the IEEE Conference on Ultra Wideband Systems and Technologies in 2002; Technical Program Vice-Chair for the IEEE International Conference on Communications in 2002; and the Tutorial Chair for ICC-2009 and the IEEE Semiannual International Vehicular Technology Conference in Fall 2001. He was the chair (2004–2006) and secretary (2002–2004) for the Radio Communications Committee of the IEEE Communications Society. Dr. Win is currently an Editor for IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS. He served as Area Editor for *Modulation and Signal Design* (2003–2006), Editor for *Wideband Wireless and Diversity* (2003–2006), and Editor for *Equalization and Diversity* (1998–2003), all for the IEEE TRANSACTIONS ON COMMUNICATIONS. He was Guest-Editor for the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS (Special Issue on Ultra-Wideband Radio in Multiaccess Wireless Communications) in 2002.

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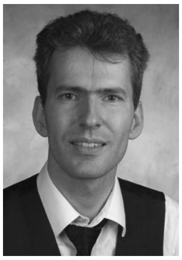
Dr. Dardari is the current Secretary for the Radio Communications Committee of the IEEE Communication Society. He was Cochair of the Wireless Communications Symposium of the IEEE ICC 2007 and of the IEEE International Conference on UWB (ICUWB) 2006. He was Guest Editor for the Proceedings of the IEEE (Special Issue on UWB Technology and Emerging Applications). Currently, he is an Editor for IEEE Transactions on Wireless Communications. He is a Reviewer for Transactions/Journals and conferences, and a Technical Program Committee member for numerous international conferences.



Andreas F. Molisch (Fellow, IEEE) received the Dipl.-Ing., Dr. Techn., and Habilitation degrees from the Technical University Vienna, Austria, in 1990, 1994, and 1999, respectively.

From 1991 to 2000, he was with the TU Vienna, becoming an Associate Professor there in 1999. From 2000 to 2002, he was with the Wireless Systems Research Department, AT&T (Bell) Laboratories Research, Middletown, NJ. From 2002–2008, he was with Mitsubishi Electric Research Labs, Cambridge, MA, most recently as Distinguished Member of Technical Staff and Chief Wireless Standards Architect; simultaneously, he was also a Professor and Chairholder for Radio Systems at Lund University, Sweden. Since 2009, he has been Professor of Electrical Engineering at the University of Southern California, Los Angeles, CA. He has conducted research in the areas of SAW filters, radiative transfer in atomic vapors, atomic line filters, smart antennas, and wide-band systems. His current research interests are measurement and modeling of mobile radio channels, UWB, cooperative communications, and MIMO systems. He has authored, coauthored, or edited four books, including "*Wireless Communications*" (New York: Wiley-IEEE Press), 11 book chapters, more than 110 journal papers, and numerous conference contributions. He has received more than 70 patents.

Dr. Molisch is an Editor of the IEEE Transactions on Wireless Communications and a Co-editor of recent or upcoming Special Issues of the *Journal of Wireless Communications and Mobile Computing*, IEEE Journal on Selected Areas in Communications, and Proceedings of the IEEE. He has been a member of numerous Technical Program Committees (TPCs), Vice Chair of the TPC of VTC 2005 spring, General Chair of ICUWB 2006, TPC Cochair of the wireless symposium of Globecomm 2007, TPC Chair of Chinacom2007, and General Chair of Chinacom 2008. He has participated in the European research initiatives COST 231, COST 259, and COST273, where he was Chairman of the MIMO channel working group. He was Chairman of the IEEE 802.15.4a channel model standardization group and is Chairman of Commission C (signals and systems) of the International Union of Radio Scientists. He is a Fellow of the IEEE, Fellow of the IET, IEEE Distinguished Lecturer, and recipient of several awards.

Werner Wiesbeck (Fellow, IEEE) received the Dipl.-Ing. (M.S.E.E.) and Dr.-Ing. (Ph.D.E.E.) degrees from the Technical University Munich, Germany, in 1969 and 1972, respectively.

From 1972 to 1983, he was with AEG-Telefunken in various positions, including Head of R&D of the Microwave Division in Flensburg and Marketing Director, Receiver and Direction Finder Division, Ulm. During this period, he had product responsibility for millimeter-wave radars, receivers, direction finders, and electronic warfare systems. From 1983 to 2007, he was Director of the Institut für Höchstfrequenztechnik und Elektronik, University of Karlsruhe (TH), where he had been Dean of the Faculty of Electrical Engineering and is now a Distinguished Scientist with the Karlsruhe Institute of Technology. His research topics include electromagnetics, antennas, wave propagation, communications, radar, and remote sensing. In 1989 and 1994, respectively, he spent a six-month sabbatical with the Jet Propulsion Laboratory, Pasadena, CA. He has been General Chairman of the 1988 Heinrich Hertz Centennial Symposium and the 1993 Conference on Microwaves and Optics (MIOP'93), Technical Chairman of the International mm-Wave and Infrared Conference 2004, Chairman of the German Microwave Conference GeMIC 2006, and a member of the Scientific and Technical Program Committees of many conferences. He is a member of an Advisory Committee of the EU Joint Research Centre (Ispra/Italy) and an Advisor to the German Research Council, to the Federal German Ministry for Research, and to industry in Germany.

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