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Edited by Thomas Zwick , Werner Wiesbeck , Jens Timmermann , Grzegorz Adamiuk
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Ultra-wideband RF System Engineering

This comprehensive summary of the state of the art in ultra-wideband (UWB) system engineering takes you through all aspects of UWB design, from components through the propagation channel to system engineering aspects.

Mathematical tools and basics are covered, allowing for a complete characterization and description of the UWB scenario, in both the time and the frequency domains. UWB MMICs, antennas, antenna arrays, and filters are described, as well as quality measurement parameters and design methods for specific applications. The UWB propagation channel is discussed, including a complete mathematical description together with modeling tools. A system analysis is offered, addressing both radio and radar systems, and techniques for optimization and calibration. Finally, an overview of future applications of UWB technology is presented.

This volume is ideal for scientists as well as for RF system and component engineers working in short range wireless technologies.

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Ultra-Wideband RF System Engineering

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Preface

For many scientists and engineers working in ultra-wideband technology, it seems that the idea of using signals with such a wide instantaneous bandwidth was spread by the US FCC with the accreditation of the frequency band from 3.1 to 10.6 GHz. But, if we look back in history, we find that even the first man-made electromagnetic waves were generated by sparks. Especially famous for electromagnetic research was Heinrich Hertz who, in the 1880s, verified the speed of propagation of electromagnetic waves, their polarization and interaction with objects, and the correct description of these waves by Maxwell's equations at our university in Karlsruhe, Germany. Before this time, electromagnetic waves could only be generated by the aforementioned sparks and were thus ultra-wideband.

Ultra-wideband was banned in the 1920s because it occupied too great a portion of the spectrum and from this point was primarily limited to military applications. This was until 1992 when Leopold Felsen, Lawrence Carin, and Henry Bertoni organized a conference on ultra-wideband, short-pulse electromagnetics in Brooklyn. Our institution, the Institut für Höchstfrequenztechnik und Elektronik (now the Institut für Hochfrequenztechnik und Elektronik) had the privilege of participating in this first conference on ultra-wideband. The topics at the conference were so fascinating that we decided to step into this area. The first research topics were in ground penetration radar, with the idea of detecting anti-personnel mines.

After the first conference a number of other colleagues stepped into the ultra-wideband area and a real ultra-wideband community was established. Since then, in our institution, numerous diploma and master's students, and also PhD candidates, have been working in the ultra-wideband area and its various applications such as radar, communications, localization and medical applications. During this time a detailed knowledge of ultra-wideband electromagnetics, components and system engineering has been developed. As usual, selected topics were published at world-leading conferences and in renowned journals, but most of the detailed results were documented in various internal reports and stored at our laboratory. In 2010 Professor Peter Russer from the Technical University in Munich encouraged us to publish this wide knowledge in a single volume and make it available for the whole community. Our motivation has been to focus on selected topics from the state of the art in ultra-wideband engineering, which will help the reader to understand and develop their ultra-wideband systems and inspire new ideas for further research in this prospective area.

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The authors and editors would like to thank all those who have supported them with ideas and research projects both before and throughout the writing of this book. In particular, we are grateful to all the diploma, master's and PhD students who contributed a major part to this book through their research and thesis projects. Special thanks go to the German Science Foundation (Deutsche Forschungsgemeinschaft) for their continuous support of our ultra-wideband research work in the UKoLoS program from 2004 to 2012 [167]. Without their funding and encouragement, neither the intensity nor the breadth of our scientific research would have been possible. Within the UKoLoS program, we have enjoyed a particularly fruitful exchange with our colleagues at the Universities of Ilmenau, Berlin, Erlangen-Nürnberg, Duisburg-Essen, Hannover and Ulm. UKoLoS was made a true success by the project's coordinator Professor Dr.-Ing. habil. Rainer Thomä of the Unversity of Ilmenau, whose progressive leadership we have greatly valued.

We would like to acknowledge that the work done by Grzegorz Adamiuk, Xuyang Li, and Jens Timmermann was undertaken during their time at Karlsruhe Institute of Technology. They have since moved to new establishments detailed in the list of contributors.

Finally, we would like to thank our various industrial partners for their support in the development of components and systems for dedicated ultra-wideband applications. We find ourselves in the very fortunate position of being able to rely on close links with German industry, and we do acknowledge that such backing can never be taken for granted. We may not have included all the valuable sponsors, contacts, and sources of ideas from which we have profited in this acknowledgment. Nevertheless, we wish to express our gratitude to all the readers of this book who may feel that they have contributed in one way or another.

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Notation

Latin symbols

$\tilde{a}$	forward propagating wave amplitude in the frequency domain
a	forward propagating wave amplitude in the time domain
A_{avg}	average level of the peak values of the received pulses
A_{W}	effective antenna area
A_{xt}	average peak level of the noise or cross-talk signal
$af(t, \psi)$	array factor in the time domain
$AF(f, \psi)$	array factor in the frequency domain
b	backward propagating wave amplitude in the time domain
$\tilde{b}$	backward propagating wave amplitude in the frequency domain
B	observation point
B	signal bandwidth
B_{a}	absolute bandwidth
B_{r}	relative bandwidth
BW	impedance bandwidth ($S_{11} < -3$ dB)
C	Shannon channel capacity
C	complex radiation pattern
d	distortion
d	distance between array elements
d	distance
D	antenna dimension
D	directivity
$\mathbf{e}$	electric field strength vector in the time domain
E_{b}	bit energy
$\mathbf{E}$	electric field strength vector in the frequency domain
$\mathbf{E}^{\mathrm{S}}$	scattered electric field strength
f	frequency
f_{c}	geometric center frequency
f_{l}	lower frequency bound
f_{u}	upper frequency bound
f_{PRF}	pulse repetition frequency
F	fidelity
g_0	Green's function of free space

g_{T}	transient gain
G	antenna gain
G_{Rx}	antenna gain of receiver
G_{Tx}	antenna gain of transmitter
h	impulse response in the time domain
h_{Rx}	height of receiver over ground
h_{Tx}	height of transmitter over ground
H	transfer function in the frequency domain
H_{G}	generator voltage transfer function
H_{ges}	overall transfer function
H_{Klm}	port voltage transfer function
$\mathbf{h}$	full polarimetric impulse response in the time domain
$\mathbf{H}$	full polarimetric transfer function in the frequency domain
$\mathbf{H}_{\mathrm{oc}}$	effective antenna height related to open circuit voltage
i	counter
i	current in the time domain
I	current in the frequency domain
j	imaginary unit $\mathrm{j} = \sqrt{-1}$
$\mathbf{j}$	current density in the time domain
$\mathbf{j}^{\delta}$	current density in the time domain related to a Dirac excitation
$\mathbf{J}$	current density in the frequency domain
k	wave number
K	constant of Wiener filter
l	length
$L_{\mathrm{FS}}(f)$	free-space attenuation
$L_{\mathrm{FS,UWB}}(f)$	free-space attenuation of UWB signal
$L_{\mathrm{two\text{-}path}}(f)$	free-space attenuation of two-path model
m	counter
M	number of positions
n	counter
N	number of elements
N	noise power
N_0	noise spectral density
N_m	number of propagation paths
N_{ortho}	number of orthogonal pulses
N_{TH}	number of time-hopping time slots
O	center of origin
$\mathrm{O_Q}$	center of radiation
p	polarimetric matching
p	peak value of impulse response
$p(t)$	pulse shape in the time domain
P_{loss}	loss
P_{rad}	radiated power

P_{refl}	reflected power
P_{Rx}	total receive power
P_{Tx}	total transmit power
Q	quality factor
Q	error function
r	radius, distance to transmitting antenna
$\tilde{r}$	reflection coefficient in the frequency domain
r_{A}	radius of smallest sphere that can contain the antenna
r_{CCF}	cross-correlation function
r_{Q}	distance from center of origin to center of radiation
r_{TxRx}	distance between transmitter and receiver
R	data rate
S	signal power density
S	signal power
S_{11}	input reflection coefficient
S_{21}	transmission coefficient
S_{12}	feedback coefficient
S_{22}	output reflection coefficient
$[\mathbf{S}]$	scattering matrix
S/H	sample and hold
t	time
T	duration in time or duration of a period
T	temperature
T_0	time step
T_{p}	pulse duration
T_{PPM}	PPM time offset
T_{TH}	length of time-hopping time slot
$\mathbf{T}_i$	transmission coefficient of polarimetric propagation path
u	voltage in the time domain
U	voltage in the frequency domain
U_{BP}	bandpass signal
U_{G}	generator open circuit voltage
U_{oc}	receiving antenna open circuit voltage
V	volume
w_i	weighting coefficient used in the time domain
W_i	weighting coefficient used in the frequency domain
Z	impedance
Z_{C}	characteristic impedance
Z_{G}	generator impedance
Z_{L}	load impedance

Greek symbols

α	fraction of peak value used in ringing definition
α	attenuation coefficient
β	phase coefficient
γ	absolute value of reflection coefficient of second path
γ	complex propagation constant
δ	Dirac impulse
Δl	path length difference
ΔR	range resolution
ε	permittivity
ε_0	free-space permittivity
ε_r'	real part of relative permittivity
ε_r''	imaginary part of relative permittivity
η	efficiency
θ	elevation angle in spherical coordinates
Θ_mb	main beam direction
λ	wavelength
λ_0	free-space wavelength at center frequency
ξ	polarimetric ratio
ρ	cross-correlation coefficient
σ	conductivity, standard deviation of the noise signal
σ	conductivity of medium
σ_G	standard deviation of G
σ_{τ_G}	standard deviation of group delay
τ	time duration or delay
$\overline{\tau}_\mathrm{D}$	average delay time
τ_DS	delay spread
τ_e	true time delay increment
τ_FWHM	duration of full width at half maximum
τ_g	group delay
τ_r	duration of ringing
τ_rad	antenna signal delay from port to far field port
τ_TOF	time of flight
ϕ	phase of reflection coefficient of second path
Φ	electric potential in the time domain
φ	phase angle
ψ	azimuth angle in spherical coordinates
ψ_mb	main beam direction
ω	angular frequency
Ω	steradian

Operators and mathematical symbols

r	scalar
$\mathbf{r}$	vector
$\mathbf{r}^{\mathrm{T}}$	vector $\mathbf{r}$ transposed
$\hat{\mathbf{r}}$	unit vector parallel $\mathbf{r}$
$\hat{\mathbf{r}}_\theta$	local base unit vector in θ-direction
$\hat{\mathbf{r}}_\psi$	local base unit vector in ψ-direction
$\hat{\mathbf{r}}_r$	local base unit vector in r-direction
	with $\hat{\mathbf{r}}_r = \hat{\mathbf{r}}$ in spherical coordinates
$\hat{\mathbf{r}}_z$	local base unit vector in z-direction ($\theta = 0$)
$\lvert\mathbf{r}\rvert$	absolute value of $\mathbf{r}$
$\mathbf{r}_1 \cdot \mathbf{r}_2$	scalar product of $\mathbf{r}_1$ and $\mathbf{r}_2$
$\mathbf{r}_1 \times \mathbf{r}_2$	vector product of $\mathbf{r}_1$ and $\mathbf{r}_2$
$r_1 * r_2$	convolution integral of r_1 and r_2
$\mathbf{r}_1 * \mathbf{r}_2$	convolution integral analog to a scalar product of $\mathbf{r}_1$ and $\mathbf{r}_2$
$[\mathbf{r}]$	matrix
$[r]$	physical unit of r
$\Re\{\cdot\}$	real part
$\mathbb{R}^3$	3D vector space
$\mathbb{R}^3 \backslash V_{\mathrm{A}}$	$\mathbb{R}^3$ without the volume V_{A}
$\mathbf{H}^+$	analytic signal of $\mathbf{H}$
$\mathbf{H}^*$	conjugate complex of $\mathbf{H}$
$\mathbf{H}^{\mathrm{T}}$	transposed matrix of $\mathbf{H}$
$\mathcal{H}\{\cdot\}$	Hilbert transform
$\lVert\mathbf{H}\rVert_p$	p-norm of $\lvert\mathbf{H}\rvert$
$\overline{G}$	integral average of G over frequency
$\lVert h(t)\rVert_2$	2-norm of $h(t)$
$\angle H$	phase angle of H
det	determinate
div $\mathbf{a}$	divergence (sources) of $\mathbf{a}$
exp	exponential function
grad a	gradient of a
ln	natural logarithm
log	logarithm to the base 10
max	maximum
min	minimum
rot $\mathbf{a}$	rotation (curls) of $\mathbf{a}$
sup	supremum
∞	infinity
$\propto$	proportional

General indices

A, ant	antenna
ar	array
BP	bandpass
co	copolarisation
feed	feed
FF	far field
FS	free space
G	generator
h	horizontal
L	load or line
mb	main beam
Mod	model
PC	propagation channel
r	radial
ref	reference
rel	relative
Rx	receiver
Tst	test
Tx	transmitter
v	vertical
x	cross-polarisation
xt	cross-talk
+	forward propagating wave
−	backward propagating wave

Constants

c_0	speed of light in vacuum: 2.997925×10^8 m/s
C	Euler–Mascheroni constant: 0.577...
e	Euler number: 2.718...
ε_0	permittivity of vacuum: 8.854×10^{-12} As/(Vm)
k	Boltzmann constant
μ_0	permeability of vacuum: $4\pi \times 10^{-7}$ Vs/(Am) $\approx 1.257\ldots \times 10^{-6}$ Vs/(Am)
π	ratio of circumference to diameter of a circle 3.1415...
Z_{F0}	wave impedance in vacuum: $Z_{F0} = \sqrt{\frac{\mu_0}{\varepsilon_0}} \approx 377\,\Omega$

Acronyms

3D	3-dimensional
ACR	auto-correlation receiver
ADC	analog–digital converter
ADS	advanced design system
AF	array factor
AIR	antenna impulse response
AoA	angle of arrival
AoD	angle of departure
AUT	antenna under test
AWGN	additive white Gaussian noise
BAN	body area network
BB	base band
BBH	broadband horn antenna
BER	bit error rate
BJT	bipolar junction transistor
BPSK	binary phase shift keying
bs	boresight
BS	base station
CAD	computer aided design
CDF	cumulative density function
CMOS	complementary metal oxide semiconductor
CPW	coplanar waveguide
CR	correlation receiver
CSL	coupled slotline
CT	computed tomography
CW	continuous wave
DAC	digital–analog converter
DC	direct current
DCO	digitally controlled oscillator
DFG	Deutsche Forschungsgemeinschaft (*German Research Foundation*)
DFT	discrete Fourier transform
DLL	delay-locked loop
DoA	direction of arrival

DoD	direction of departure
DOP	dilution of precision
DS	delay spread
DUT	device under test
ECC	Electronic Communications Committee
ECG	electrocardiogram
EF	element factor
EIRP	equivalent isotropically radiated power
EM	electromagnetic
ESD	electrostatic discharge
EuMA	European Microwave Association
EurAAP	European Association on Antennas and Propagation
FBW	fractional bandwidth
FCC	Federal Communications Commission
FD	frequency domain
FDTD	finite difference time domain
FFT	fast Fourier transform
FIR	finite impulse response
FPGA	field programmable gate array
FR	flashing receiver
FWHM	full width at half maximum
GDOP	geometrical dilution of precision
HDOP	horizontal dilution of precision
HPIB	Hewlett Packard interconnect bus
IC	integrated circuit
ICU	intensive care unit
IEE	Institution of Electrical Engineers, part of IET since 2007
IEEE	Institute of Electrical and Electronics Engineers
IET	Institution of Engineering and Technology
IFFT	inverse fast Fourier transformation
IHE	Institut für Hochfrequenztechnik und Elektronik at KIT
IHP	Innovations for High Performance Microelectronics (Research Institute of the Leibniz Association in Frankfurt/Oder, Germany)
IIR	infinite impulse response
INS	inertial navigation system
IR	impulse response
IR-UWB	impulse radio ultra-wideband
ISI	inter-symbol interference
ISO	International Organization for Standardization
KIT	Karlsruhe Institute of Technology
lhc	left-hand circular
LMS	least mean square
LNA	low-noise amplifier

LO	local oscillator
log-per	logarithmic periodic antenna
LOS	line-of-sight
LPDA	logarithmic periodic dipole array
LR	left–right
LTI	linear time invariant
LU	lower–upper
LUT	look-up table
MAC	multiple access
MBM	measurement data-based model
MIKON	International Conference on Microwaves, Radar & Wireless Communications
MIMO	multiple input multiple output
ML	maximum length
MOSFET	metal oxide semiconductor field-effect transistor
MRI	magnetic resonance imaging
MU	mobile unit
MW	microwave
NESP	normalized effective signal power
NLOS	non-line-of-sight
OFDM	orthogonal frequency division multiplexing
OOK	on–off keying
OPM	orthogonal pulse modulation
PA	power amplifier
PCB	printed circuit board
p-cg	p-center of gravity
PDF	probability density function
PDP	power delay profile
PEG	polyethylene glycol
PG	pulse generator
PGA	programmable gain amplifier
PGC	programmable gain control
PGEN	pulse generator
PLL	phase locked loop
PN	pseudo noise
PPM	pulse position modulation
PRF	pulse repetition frequency
PSD	power spectral density
PVC	polyvinyl chloride
PVT	process, voltage and temperature
RAIM	receiver autonomous integrity monitoring
RCM	range comparison method
RCS	radar cross-section

RF	radio frequency
RFID	radio frequency identification
rhc	right-hand circular
RMS	root mean square
RSS	received signal strength
Rx	receiver
SAR	synthetic aperture radar
SER	symbol error rate
SIB	system interconnect bus
SISO	single-input single-output
SMA	sub-miniature plug type A
SNR	signal-to-noise ratio
SPI	serial peripheral interface
SRD	step recovery diode
STR	signal to threshold ratio
SVR	support vector regression
TD	time domain
TDC	time-to-digital converter
TDMA	time division multiple access
TDoA	time difference of arrival
TEM	transversal electric magnetic
TH	time-hopping
ToA	time of arrival
TOF	time of flight
TR	transmitted reference
TTD	true time delay
TWR	two-way ranging
Tx	transmitter
US	United States
UWB	ultra-wideband
VCO	voltage controlled oscillator
VDOP	vertical dilution of precision
VGA	variable gain amplifier
VNA	vector network analyzer
VSWR	voltage standing wave ratio
WBAN	wireless body area networks
WLAN	wireless local area network