Microwave and Wireless Measurement Techniques

From typical metrology parameters for common wireless and microwave components to the implementation of measurement benches, this introduction to metrology contains all the key information on the subject. Using it, readers will be able to

- interpret and measure most of the parameters described in a microwave component's datasheet
- understand the practical limitations and theoretical principles of instrument operation
- combine several instruments into measurement benches for measuring microwave and wireless quantities

Several practical examples are included, demonstrating how to measure intermodulation distortion, error-vector magnitude, *S*-parameters, and large-signal waveforms. Each chapter ends with a set of exercises, allowing readers to test their understanding of the material covered and making the book equally suited for course use and for self-study.

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"This is a text book that every practicing engineer would like to carry into the RF/ microwave laboratory. Written by two known experts in microwave nonlinear measurements, it covers the wide spectrum of microwave instrumentation from the basic definitions of the circuit's figures of merit to the more evolved and up-to-date material of digital/analog and time/frequency instruments and excitation design."
Jose Carlos Pedro, Universidade de Aveiro, Portugal

"This book provides an excellent foundation for those wanting to know about contemporary measurement techniques used in wireless and microwave applications. The authors have used both their considerable knowledge of the subject matter along with many years' teaching experience to provide a clear and structured approach to these subject areas. This book is therefore ideally suited as a foundation text for lectures and/or training courses in this area, aimed at graduate level students and professional engineers working in this industry."
Nick Ridler, IET Fellow

"Comprehensive, focussed and immediately useful, this book is an excellent resource for all engineers who want to understand and measure the performance of wireless components and systems."
Uwe Arz, Physikalisch-Technische Bundesanstalt (PTB), Germany

Preface

Metrology has been the most important aspect of wireless communication ever since the time of Maxwell and Hertz at its very beginning. In fact, the metrology aspects related to radio communications have for decades been one of the driving forces for progress in radio communication. For instance, radar is nothing more than a very good measurement instrument that can be used in important applications such as target identification. Nevertheless, most wireless systems nowadays depend heavily on metrology and thus measurement, for instance new spectrum management, QoS evaluation and green RF technologies, since they are all supported in high-quality wireless radio components. That is why it is important to understand the figures of merit of the main wireless system components, how to measure them, and how to model them. Moreover, with recent advances in software-defined radio, and in future cognitive radio, measurements in time/frequency/analog/digital domains have become a very important problem to microwave and RF engineers. This book is aimed to give engineers and researchers answers at the beginning of their laboratory adventures in microwave, wireless systems and circuits. It can also be used in connection with a graduate class on measuring wireless systems, or a professor can select parts of the book for a class on wireless systems in the broad sense. The main idea is to have a text that allows the correct identification of the quantities to be measured and their meaning, allows one to understand how to measure those quantities, and allows one to understand the differences between excitation signals, and between instruments, and between quantities to be measured in different domains (time, frequency, analog, and digital). Along this path to completeness the authors expect to give an overview of the main quantities and figures of merit that can be measured, how to measure them, how to calibrate the instruments, and, finally, how to understand the measurement results. Measurements in different domains will also be explained, including the main drawbacks of each approach. The book will thus be organized as follows.

In Chapter 1 the idea is to present to the reader the main important instrumentation and measurable figures of merit that are important for wireless transceivers. We hope that the reader will understand precisely these main figures of merit and the strategies for characterization and modeling. Some information that will facilitate the reading of typical commercial datasheets and the understanding of the most important figures of merit presented on those documents will also be given.

In chapter 2 the instrumentation typically used for wireless transceiver characterization will be presented, especially that involved with radio signals. The instruments will be presented considering the typical figures of merit described in Chapter 1.

No measurement instrumentation can work without the need for appropriate excitation, so in Chapter 3 we will present the most important excitations for radio characterization, namely those mainly supported in sinusoidal excitations.

In Chapter 4 the main idea is to present several test benches for modeling and characterization that allow a correct identification of several linear and nonlinear parameters useful for wireless systems.

The work of writing and publishing this book is not exclusively that of the authors, but includes the help and collaboration of many persons who came into our lives during this process of duration almost 4 years. So we would like to express our gratitude to the many people who, directly or indirectly, helped us to carry out this task.

The first acknowledgments go to our families for their patience and emotional support. In addition we are especially in debt to a group of our students, or simply collaborators, who contributed some results, images, and experimental data to the book. They include Pedro Miguel Cruz, Diogo Ribeiro, Paulo Gonçalves, Hugo Cravo Gomes, Alirio Boaventura, Hugo Mostardinha, Maciej Myśliński, and Gustavo Avolio, among others. Finally we would like to acknowledge Dr. Kate Remley from the National Institute of Standards and Technology (NIST) for the initial ideas for the book, the financial and institutional support provided by the Portuguese National Science Foundation (FCT), the Instituto de Telecomunicações, Departamento de Electrónica, Telecomunicações e Informática of the Universidade de Aveiro, as well as the FWO-Flanders.

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More information

Notation

(I)	unit matrix
$\delta(\ )$	Dirac function
η	efficiency
η_e	effective efficiency
$\Gamma(x)$	reflection coefficient
Γ_{IN}	input reflection coefficient
Γ_{OPT}	optimum source-reflection coefficient for minimum noise figure
Γ_{OUT}	output reflection coefficient
ω	pulsation
$\phi(t)$	modulated phase
σ	error variance
a	incident traveling voltage wave
ACPR	adjacent-channel power ratio
$\mathrm{ACPR_L}$	lower adjacent-channel power ratio
$\mathrm{ACPR_T}$	total adjacent-channel power ratio
$\mathrm{ACPR_U}$	upper adjacent-channel power ratio
$\mathrm{ACPR_{SP}}$	spot adjacent-channel power ratio
b	scattered traveling voltage wave
C_S	correlation matrix in terms of S-parameters
C_Y	correlation matrix in terms of Y-parameters
DR	dynamic range
$E(t)$	energy variation over time
E_s	energy source
F	noise factor
f	frequency
f_0	fundamental frequency
F_{MIN}	minimum noise factor
G	operating power gain
G_A	available power gain
G_T	transducer power gain
I	current
i	instantaneous current
$i(t)$	instantaneous current over time
I_D	diode current

I_{D0}	diode bias current
IIP_3	input third-order intercept point
IP_3	third-order intercept point
IP_{1dB}	1-dB-compression point referred to the input
k_B	Boltzmann constant
L	conversion loss
NF	noise figure
$P(t)$	power variation over time
P_R	power dissipated over a resistance R
P_s	source power
P_{1dB}	1-dB-compression point
P_{DC}	DC power
P_{diss}	dissipated power
P_{gi}	incident measured power
P_{IMD}	intermodulation distortion power
P_i	incident power
P_{LA}	total power in lower adjacent-channel band
P_{sat}	saturated output power
P_{UA}	total power in upper adjacent-channel band
q	charge of an electron
R	resistance
R_N	noise resistance
S-parameters	scattering parameters
S_i	sensitivity
ST	sweep time
T	temperature
T	time window (period)
t_r	rise time
V	voltage
v	instantaneous voltage
$v(t)$	instantaneous voltage over time
V_D	diode voltage
V_T	thermal voltage
$V_{D_{Bias}}$	diode bias voltage
Y-parameters	admittance parameters
Y_{OPT}	optimum source admittance for minimum noise figure
Z-parameters	impedance parameters
Z_0	characteristic impedance
Z_L	load impedance
Z_S	source impedance

Abbreviations

ADC	analog-to-digital converter
AM	amplitude modulation
ASIC	application-specific integrated circuit
AWG	arbitrary-waveform generator
BPF	bandpass filter
ccdf	complementary cumulative distribution function
CCPR	co-channel power ratio
CF	calibration factor
CR	cognitive radio
CRT	cathode-ray tubes
CW	carrier wave
DAC	digital-to-analog converter
dB	decibel
dBc	decibels below carrier
DC	direct current
DDS	direct digital synthesis
DFS	direct frequency synthesis
DSP	digital signal processor
DUT	device under test
emf	electromotive force
ENBW	equivalent noise bandwidth
ENOB	effective number of bits
EVM	error-vector magnitude
FDM	frequency-division multiplex
FFT	fast fourier transform
FOM	figure of merit
FPGA	field-programmable gate array
GA	generic amplifier
IF	intermediate frequency
IIP3	third-order intercept point referred to the input
IMD	intermodulation distortion
IMR	intermodulation ratio
LNA	low-noise amplifier
LO	local oscillator

LSB	least significant bit
M-IMR	multi-sine intermodulation ratio
MIMO	multiple input, multiple output
MSB	most-significant bit
NBGN	narrowband Gaussian noise
NPR	noise power ratio
NVNA	nonlinear vector network analyzer
OCXO	oven-controlled oscillator
OFDM	orthogonal frequency-division multiplexing
OSR	over-sample ratio
PA	power amplifier
PAE	power added efficiency
PAPR	peak-to-average power ratio
pdf	probability density function
PLL	phase-locked loop
PM	phase modulation
PSD	power spectral density
QPSK	quadrature phase-shift keying
RBW	resolution bandwidth
RF	radio frequency
RL	return loss
RMS	root mean square
RTSA	real-time signal analyzer
SA	spectrum analyzer
SDR	software-defined radio
SFDR	spurious free dynamic range
SINAD	signal-to-noise-and-distortion
SNR	signal-to-noise ratio
SNR_ADC	signal-to-noise ratio for ADCs
SSB noise	single-sideband noise
STFT	short-time Fourier transform
SUT	system under test
TCXO	temperature-compensated crystal oscillator
TDD	time-division duplex
THD	total harmonic distortion
ULG	underlying linear gain
VCO	voltage-controlled oscillator
VGA	variable-gain amplifier
VNA	vector network analyzer
VSA	vector signal analyzer
VSWR	voltage standing-wave ratio
YIG	yttrium iron garnet