

CIRCUIT THEORY AND COMMUNICATION

MICHEL T. IVRLAČ

LECTURE NOTES



Technische Universität München
Associate Professorship for Methods of Signal Processing

Berichte aus der Kommunikationstechnik

Michel Ivrlač

Circuit Theory and Communication

Shaker Verlag
Aachen 2017

Bibliographic information published by the Deutsche Nationalbibliothek

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at <http://dnb.d-nb.de>.

Copyright Shaker Verlag 2017

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publishers.

Printed in Germany.

ISBN 978-3-8440-4974-9

ISSN 0945-0823

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen

Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9

Internet: www.shaker.de • e-mail: info@shaker.de

This book contains part of the *habilitation* thesis of
PD Dr.-Ing. Michel T. Ivrlač. He worked for habilitation during 2008–2013
at the Institute for Circuit Theory and Signal Processing of the
Technische Universität München (TUM).

The committee members were Prof. Dr. techn. Josef A. Nossek (TUM),
Univ. Prof. Dr.-Ing. Berthold Lankl (Armed Forces University Munich) and
Univ. Prof. Dr. Rudolf Mathar (RWTH Aachen).

PD Dr.-Ing. Michel T. Ivrlač earned his *Facultas Docendi* for
»Netzwerktheorie für Kommunikation« on 04. December 2013, and was
granted his *Venia Legendi* on 31. July 2014, both from TUM.

This book serves as the principle text for the graduate course in
»Circuit Theory and Communication«
that Dr. Ivrlač teaches at TUM since winter 2008.

I dedicate this book to
my wife *Lai-U* and our children *Gallus* and *Felina*.



CONTENTS

1	Introduction and Overview	1
1.1	Energy of Scalar Signals	3
1.2	Energy of Vector Signals	4
1.3	On the Assignment of Physical Meaning	7
1.3.1	Scalar Signals	8
1.3.2	Vector Signals	12
1.4	Modeling Consistently with Physics	18
1.5	Multipoint Communication Systems	19
1.6	Multistreaming	27
1.7	Compact Multi-Antenna Systems	29
1.8	Getting the Physics Right	33
2	Terminals, Ports and Multiports	35
2.1	Voltage, Current and Power	36
2.2	Dissipation, Passivity and Losslessness	41
2.3	Basic Oneports	44
2.4	Linear Multiports as Black Boxes	46
2.4.1	Regular Multiports	47
2.4.2	Matrix Impulse Response Descriptions	49
2.4.3	Impedance- and Admittance Matrix Impulse Response	55
2.4.4	Chain Matrix Impulse Response	56
2.4.5	Frequency Domain Representation	57
2.4.6	Implicit Description	59
2.4.7	Impulse Response from AC-Analysis	60
2.4.8	Passivity of Regular Linear Time-invariant Multiports	65
2.5	Scattering Formalism	73
2.6	Reciprocity	78
3	Linear Twoport Communication Systems	81
3.1	Complex Envelope Representation	82
3.1.1	Complex Envelopes	83

3.1.2	The Hilbert Transform	85
3.1.3	Impulse Responses with Complex Envelopes	86
3.1.4	Narrow-band Complex Envelope	87
3.1.5	Quadrature Amplitude Modulator / Demodulator	88
3.2	Noiseless Narrow-band Communication System	90
3.3	Transmit Power	92
3.4	Noisy Communication System	94
3.4.1	Noisy Twoports	94
3.4.2	Statistical Noise Model	97
3.4.3	Noisy Receiver Model	100
3.4.4	Transmit Amplifier Model	101
3.5	Obtaining the Noise Parameters	101
3.5.1	Thermal Equilibrium Noise	102
3.5.2	Non-Equilibrium Noise	106
3.5.3	Noise Analysis with SPICE	108
3.6	Continuous-Time Twoport Communication System	111
3.7	Discrete-Time Twoport Communication System	113
3.8	Summary	122
4	Wireless Multiport Communication Systems	125
4.1	Multiport Model for Radio Communications	125
4.1.1	Impedance Matching Multiports	126
4.1.2	Antenna Multiport	128
4.1.3	Noise	129
4.1.4	The Unilateral Approximation	131
4.1.5	Input-Output Relationship	132
4.1.6	Transmit Power	133
4.1.7	Noise Covariance	135
4.2	The Antenna Multiport	135
4.2.1	Radiated power	137
4.2.2	Antenna Array Impedance Matrix	141
4.2.3	Uniform Linear Array of Isotropic Antennas	144
4.2.4	Isotropic Antennas vs. Hertzian Dipoles	145
4.2.5	The Transimpedance Matrix	146

4.3	Array Gain	148
4.3.1	Transmit Array Gain	150
4.3.2	Noise Matching	155
4.3.3	Receive Array Gain	164
4.3.4	On Scaling Laws of Signal to Noise Ratio	168
4.4	Multi-Input Multi-Output Systems	170
4.4.1	The Channel Matrix	171
4.4.2	Matched Systems with Isotropic Background Noise	172
4.4.3	Justification of the Unilateral Approximation	174
4.4.4	Channel Rank of Compact Antenna Arrays	176
A	The Ideal Twoport Transformer	185
A.1	Multiport Inductances	185
A.2	Idealization of the Twoport Transformer	187
B	Complex Numbers	191
B.1	The Imaginary Unit	191
B.2	Polar Form	192
B.3	Cotes-Euler Formula	193
B.4	Exponential Notation	195
B.5	Complex Conjugation	195
B.6	Complex Exponential and Logarithm	196
C	The Fourier Transform	197
C.1	The Fourier Integral	197
C.2	Important Properties	199
D	The Statistical Properties of Complex Baseband Noise	207
D.1	Wide-band Noise	207
D.2	Post-QAD Noise Statistics	209
D.3	Statistics of Complex Envelope Noise	216
D.4	Summary	220
E	Maximizing the Rayleigh Quotient	221
E.1	The Rayleigh Quotient	221

E.2	Maximization	222
E.3	Important Special Case	225
F	Unconditional Stability of Linear Twoports	227
F.1	Passivity of Linear Oneports	227
F.2	Stability and Passivity	228
F.3	Checking for Unconditional Stability	229
G	Passive Oneports and Analytic Functions	235
G.1	Analytic Functions	235
G.2	Integrals in the Complex Plane	240
G.3	Loop Integrals of Analytic Functions	241
G.4	Cauchy Integral Theorem	244
G.5	Complex Triangular Inequality	247
G.6	Maximum Magnitude Theorem	248
G.7	Real-part Extremal Theorem	249
G.8	A Passivity Theorem for Oneports	250
H	Transmission Lines as Twoports	253
H.1	Chain Matrix Description	254
H.2	Characteristic Impedance and Propagation Factor	258
H.3	Impedance Impulse Response	263
H.4	Physical Interpretation	264
I	The Great Laws of Conservation	269
I.1	The Principles of Classical Mechanics	269
I.1.1	Lagrangian Function	269
I.1.2	Principle of Least Action	270
I.1.3	Lagrangian Equivalence	272
I.1.4	Homogeneity, Isotropy and Galilean Invariance	274
I.2	Lagrangian of Mechanical Systems	275
I.2.1	Free Particle	275
I.2.2	The Mass of a Particle	278
I.2.3	Closed System of Particles	278
I.2.4	Kinetic and Potential Energy	280

I.2.5	Newton's Law of Motion	281
I.2.6	Open System of Particles	282
I.3	Conservation Laws	283
I.3.1	Conservation of Energy	284
I.3.2	Conservation of Momentum	286
I.3.3	Conservation of Angular Momentum	287
I.4	The Big Picture	289