Second Edition

Power Line Communications

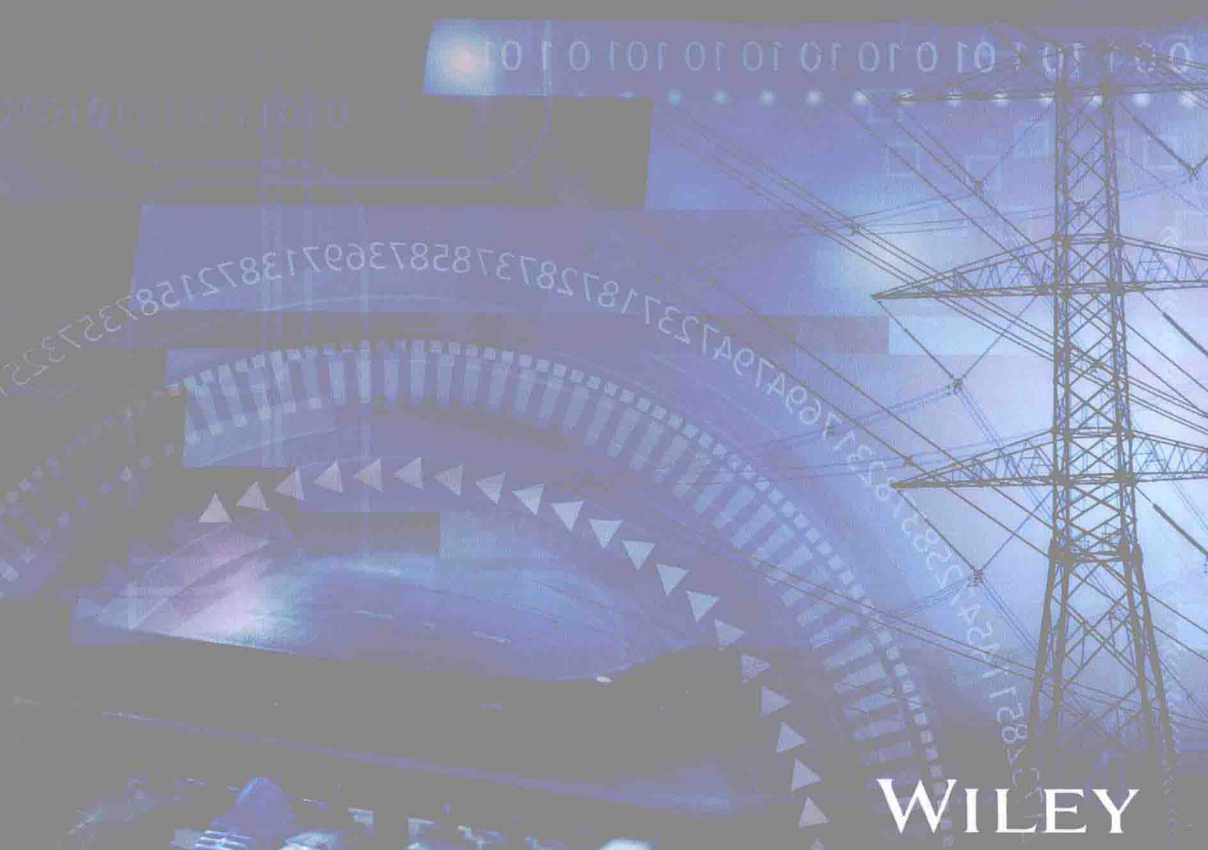
Principles, Standards and Applications from Multimedia to Smart Grid

Edited By

Lutz Lampe

Andrea M. Tonello

Theo G. Swart



WILEY

POWER LINE COMMUNICATIONS

PRINCIPLES, STANDARDS AN APPLICATIONS FROM MULTIMEDIA TO SMART GRID

Second Edition

Edited by

Lutz Lampe, Andrea M. Tonello, and Theo G. Swart

WILEY

This edition first published 2016

First Edition published in 2010

Registered office
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

Library of Congress Cataloging-in-Publication Data

Names: Lampe, Lutz, editor. | Tonello, Andrea M., editor. | Swart, Theo G., editor.
Title: Power line communications : principles, standards and applications from multimedia to smart grid / [edited by] Lutz Lampe, Andrea M. Tonello, Theo G. Swart.
Description: Second edition | Chichester, UK ; Hoboken, NJ : John Wiley & Sons, 2016. | Includes index. | Previously published as: Power line communications : theory and applications for narrowband and broadband communications over power lines, 2010.
Identifiers: LCCN 2015048934| ISBN 9781118676714 (cloth) | ISBN 9781118676776 (epub)
Subjects: LCSH: Electric lines–Carrier transmission. | Broadband communication systems.
Classification: LCC TK5103.15 .P695 2016 | DDC 621.382–dc23
LC record available at http://lccn.loc.gov/2015048934

A catalogue record for this book is available from the British Library.

Set in 10/12pt Times by Aptara Inc., New Delhi, India
Printed and bound in Malaysia by Vivar Printing Sdn Bhd

1 2016

POWER LINE COMMUNICATIONS

List of Contributors

Iñigo Berganza, Iberdrola, Section 9.1, 9.4

Gerd Bumiller, Hochschule Ruhr West – University of Applied Sciences, Chapter 7, Section 9.1

Francisco J. Cañete, University of Málaga, Section 2.3.1, 2.3.3, 2.9.2

José A. Cortés, University of Málaga, Section 6.4

Anand Dabak, Texas Instruments, Section 9.3

Salvatore D'Alessandro, University of Udine, Section 6.4

Le Phu Do, Dresden University of Technology, Section 6.2, 6.3

Klaus Dostert, Karlsruhe Institute of Technology, Section 2.3.1, 2.3.2, 5.2.2

Stefano Galli, Assia Inc., Section 2.2, Chapter 8

Mauro Girotto, University of Udine, Section 5.5

George Hallak, Hochschule Ruhr West – University of Applied Sciences, Chapter 7

Holger Hirsch, University of Duisburg-Essen, Section 3.1 to 3.6 (except 3.5.3)

Masaaki Katayama, Nagoya University, Section 2.7

Cornelis J. Kikkert, James Cook University, Chapter 4

Michael Koch, devolo AG, Section 3.1 to 3.6 (except 3.5.3)

Lutz Lampe, University of British Columbia, Editor, Section 2.8, 5.5, 6.5, Chapter 10

Haniph Latchman, University of Florida, Chapter 8

Ralf Lehnert, Dresden University of Technology, Section 6.2, 6.3, 9.1

Martine Lienard, University of Lille, Section 2.9.2

Sina Mashayekhi, University of British Columbia, Section 2.4

Anil Mengi, devolo AG, Section 9.2, 9.3

Dave G. Michelson, University of British Columbia, Section 2.4

Marcel Nassar, The University of Texas at Austin, Section 2.7

Moslem Noori, University of British Columbia, Section 6.5

Fabienne Nouvel, Institut d'Electronique et de Télécommun. de Rennes, Chapter 10

Vladimir Oksman, Lantiq, Chapter 8

Riccardo Pighi, Selta Group, Section 2.5

Antti Pinomaa, Lappeenranta University of Technology, Section 2.9.1

Gautham Prasad, University of Florida, Chapter 8

Riccardo Raheli, University of Parma, Section 5.2

Marco Raugi, University of Pisa, Section 2.9.3

David Rieken, Aclara, Section 5.4

Alberto Sendin, Iberdrola, Section 9.1, 9.4

Theo G. Swart, University of Johannesburg, Editor, Section 5.8

Andrea M. Tonello, University of Klagenfurt, Editor, Section 2.3.3, 2.6, 2.8, 5.3, 5.5, 6.4, 6.5

Mauro Tucci, University of Pisa, Section 2.9.3

Fabio Versolatto, WiTiKee, Section 2.6

A. J. Han Vinck, University of Duisburg-Essen, Section 5.2.1

Stephan Weiss, University of Strathclyde, Section 5.7

Nico Weling, devolo AG, Section 3.5.3

Lawrence W. Yonge III, Qualcomm Atheros, Inc., Chapter 8

Ahmed Zeddam, France Telecom, Orange Labs, Section 3.7

Preface

This book is the second edition of *Power Line Communications: Theory and Applications for Narrowband and Broadband Communications over Power Lines* published in 2010. As for the first edition, it has been our intention to present the most comprehensive coverage of the technical field of power line communications (PLC) that is available in a single publication. The scope of this book is uniquely wide, not only for a book on PLC. Compared to the first edition, the content has been updated and in part restructured. In particular, we have significantly expanded the part dedicated to applications of PLC, which is attributed to the further maturity of PLC technology in terms of consolidated specifications and standards and also reflected in the modification of the subtitle for this edition. Furthermore, recent innovations and changes related to channel characterization, transmission techniques and regulation are included in this edition.

The target audience for the book comprises both newcomers to the exciting field of PLC as well as researchers and practitioners already familiar with PLC. For the former, the book is intended to provide a fairly comprehensive yet readable introduction. For the latter, we expect the book to serve as an authoritative point of reference for information widely dispersed in the literature.

During the writing of this second edition, we involved 42 technical contributors from 29 institutions and 12 countries. Coordination was a huge task, almost more so than for the first edition. The editors would like to express their sincere thanks to all the contributors.

List of Acronyms

AC	Alternating Current
ACF	Autocorrelation Function
ACG	Average Channel Gain
AF	Amplify-and-forward
AM	Amplitude Modulation
AMI	Advanced Metering Infrastructure
AMN	Artificial Mains Network
AMR	Automatic Meter Reading
ARIB	Association of Radio Industries and Businesses
AU	Allocation Unit
AVLN	AV Logical Network
AWGN	Additive White Gaussian Noise
BB	Broadband
BER	Bit Error Ratio
BPL	Broadband Over Power Lines
B-PLC	Broadband PLC
BPRS	Binary Pseudo-random Sequence
BPSK	Binary Phase-shift Keying
BS	Base Station
CA-Msg	Channel Announcement Message
CAN	Controller Area Network
CB-FMT	Cyclic Block Filtered Multitone Modulation
CCDF	Complementary Cumulative Distribution Function
CCo	Central Coordinator
CDCF	Commonly Distributed Coordination Function
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CE	Conformité Européenne
CEI	Customer-end Inverter
CENELEC	Comité Européenne de Normalisation Electrotechnique
CFP	Contention Free Period
CFR	Channel Frequency Response
CISPR	International Special Committee on Radio Interference
CM	Common Mode *or* Connection Manager

CP	Cyclic Prefix *or* Contention Period
CPE	Customer Premise Equipment
CRC	Cyclic Redundancy Check
CSI	Channel State Information
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DBPSK	Binary DPSK
DCA	Dynamic Channel Allocation
DCT	Discrete Cosine Transform
DF	Decode-and-Forward
DFT	Discrete Fourier Transform
DLL	Data Link Layer
DM	Differential Mode *or* Domain Master
DPSK	Differential Phase Shift Keying
DQPSK	Quaternary DPSK
DSL	Digital Subscriber Line
DSM	Demand Side Management
DSSS	Direct Sequencing Spread Spectrum
DSTBC	Distributed Space-time Block Codes
DT	Direct Transmission
DWMT	Discrete Wavelet Multitone
EC	European Commission
ECC	Error Correction Code
ECU	Electronic Controlled Unit
EIB	European Installation Bus
EMC	Electromagnetic Compatibility
ETSI	European Telecommunications Standards Institute
EU	European Union
EUT	Equipment Under Test
EV	Electric Vehicle
FB	Filter Bank
FCC	Federal Communications Commission
FD	Frequency Domain
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FH	Frequency Hopping
FIR	Finite Impulse Response
FMT	Filtered Multitone
FSK	Frequency-shift Keying
HDCU	High Data Rate Central Control Unit
HD-PLC	High-definition Power Line Communication
HDR	High Data Rate
HDTV	High Definition Television
HF	High-frequency
HPAV	HomePlug AV

HV	High Voltage, 66 kV and above
ICI	Inter-carrier Interference
IDFT	Inverse DFT
IEC	International Electrotechnical Commission
IFFT	Inverse Fast Fourier Transform
IGBT	Insulated Gate Bipolar Transistors
IH	In-home
IN	Impulse Noise
INL	Interfering Network List
IP	Internet Protocol *or* Integer Programming
IPTV	Internet Protocol Television
ISI	Inter-symbol Interference
ISN	Impedance Stabilization Network
ISP	Inter-system Protocol
ITU	International Telecommunication Union
LAN	Local Area Network
LCL	Longitudinal Conversion Loss
LDCU	Low Data Rate Central Control Unit
LDPC	Low-density Parity-check
LDR	Low Data Rate
LLR	Log-likelihood Ratio
LMS	Least Mean Square
LP	Linear Programming
LPTV	Linear Periodically Time Variant
LTI	Linear Time Invariant
LV	Low Voltage, 110 V to 400 V
LVDC	Low-voltage Direct Current
MAC	Medium Access Control
MAI	Multiple Access Interference
MC	Multicarrier
MDCU	Multiple Data Rate Central Control Unit
MDU	Multi Dwelling Unit
MF	Matched Filter
MIMO	Multiple-input Multiple-output
MLD	Maximum-likelihood Detection
MMSE	Minimum Mean Square Error
MMU	Master Monitoring Unit
MTL	Multi-conductor Transmission Line
MV	Medium Voltage, 7.2 kV to 33 kV
MWR	Multi-way Relaying
NB	Narrowband
OAF	Opportunistic AF
ODF	Opportunistic DF
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OH	Overhead

OOB	Out of Band
OOK	On-off Keying
OPERA	Open PLC European Research Alliance
OQAM	Offset Quadrature Amplitude Modulation
OSI	Open Systems Interconnection
OSTBC	Orthogonal Space-time Block Codes
PAM	Pulse Amplitude Modulation
PDF	Probability Density Function
PHY	Physical
PLC	Power Line Communication
PLCP	Physical-layer Convergence Protocol
PoE	Power over Ethernet
PR	Perfect Reconstruction
PSD	Power Spectral Density
PSK	Phase Shift Keying
PTC	Positive Temperature Coefficient
PVC	Polyvinylchloride
QAM	Quadrature Amplitude Modulation
QC-LDPC	Quasi-cyclic Low-density Parity-check
QoS	Quality of Service
RF	Radio Frequency
RMS-DS	Root-mean-square Delay Spread
ROBO	Robust Modulation
RS	Reed-Solomon
RX	Receiver
SFN	Single Frequency Networking
SINR	Signal-to-noise and Interference Ratio
SISO	Single-input Single-output
SNR	Signal-to-noise Ratio
SST	Spread Spectrum Techniques
STBC	Space-time Block Coding
STFT	Short Time Fourier Transform
SVD	Singular Value Decomposition
TCL	Transverse Conversion Loss
TCTL	Transverse Conversion Transfer Loss
TDM	Time Division Multiplex
TDMA	Time Division Multiple Access
TEM	Transverse Electromagnetic
TF	Time Frame
T-ISN	T-shaped Impedance Stabilization Network
TL	Transmission Line
TS	Time Slot
TWR	Two-way Relaying
TX	Transmitter
TXOP	Transmission Opportunities
UDP	User Datagram Protocol

UPA	Universal Powerline Association
UTP	Unshielded Twisted Pair
UWB	Ultra Wide Band
VDSL	Very High Bit Rate Digital Subscriber Line
VLF	Very Low Frequency
VoIP	Voice Over Internet Protocol
WLAN	Wireless Local Area Network

Contents

List of Contributors xvii

Preface xix

List of Acronyms xxi

1 Introduction 1
L. Lampe, A. M. Tonello, and T. G. Swart

1.1 What is a Name? 1
1.2 Historical Notes 2
1.3 About the Book 4
References 5

2 Channel Characterization 8
F. J. Cañete, K. Dostert, S. Galli, M. Katayama, L. Lampe, M. Lienard, S. Mashayekhi, D. G. Michelson, M. Nassar, R. Pighi, A. Pinomaa, M. Raugi, A. M. Tonello, M. Tucci, and F. Versolatto

2.1 Introduction 8
2.2 Channel Modeling Fundamentals 9
2.2.1 Brief Review of Indoor/Outdoor Topologies 11
2.2.1.1 Low, Medium, and High Voltage Mains Topologies 11
2.2.1.2 Residential and Business Indoor Wiring Topologies 12
2.2.2 Some Fundamental Definitions and Properties of Band-limited Channels 15
2.2.2.1 Impulse Response Duration 16
2.2.2.2 Average Channel Gain 16
2.2.2.3 Root Mean Square Delay Spread (RMS-DS) 17
2.2.3 Characteristics of the Indoor Channel in the HF and VHF Bands 17
2.2.4 Characteristics of Outdoor Channel (LV and MV) 21
2.2.5 Characteristics of the Low Frequency Channel and its Impedance 22
2.2.6 Fundamental Approaches: Deterministic and Empirical Models 22
2.2.6.1 Time-domain Based Modeling: The Multi-path Model 22
2.2.6.2 Frequency-domain Based Modeling: Transmission-Line Models 24

2.2.7 *Advantages and Disadvantages of Modeling Approaches* 28
2.2.8 *Merging the Deterministic and the Statistical Approaches: Towards a Hybrid Model* 29
2.3 Models for Low Voltage (LV) Channels: Outdoor and Indoor Cases 30
2.3.1 *Some Fundamentals of Transmission Line Theory* 31
2.3.1.1 *Weakly Lossy Lines* 32
2.3.1.2 *Reflections* 34
2.3.2 *Models for Outdoor LV Channels* 35
2.3.2.1 *Access Network Topologies in Europe, Asia, and USA* 35
2.3.2.2 *Echo-based Channel Model* 38
2.3.2.3 *Differences for the Low Frequency Range 9–500 kHz* 48
2.3.2.4 *Reference Channel Definition for the Access Domain* 52
2.3.3 *Models for LV Indoor Channels* 53
2.3.3.1 *Modeling Principles* 54
2.3.3.2 *LTI Channel Model* 57
2.3.3.3 *LPTV Channel Model* 62
2.3.3.4 *Reference Channels Definition for In-home* 72
2.4 Models for Medium Voltage (MV) Channels 76
2.4.1 *The Medium Voltage Scenario* 77
2.4.1.1 *Distribution Substations* 77
2.4.1.2 *Network Layout and Topologies* 78
2.4.1.3 *Overhead Lines and Underground Cables* 80
2.4.1.4 *Overhead Lines* 80
2.4.1.5 *Underground Cables* 82
2.4.2 *Medium Voltage Channel Models* 84
2.4.3 *Measurement-based Characterization of MV Channels* 84
2.4.4 *Theory-based Characterization of MV Channels* 86
2.4.4.1 *Overhead Lines* 86
2.4.4.2 *Underground Cables* 86
2.4.4.3 *MIMO PLC in MV Networks* 87
2.4.5 *Noise and Interference* 88
2.5 Models for Outdoor Channels: High Voltage Case 88
2.5.1 *High Voltage Scenario* 88
2.5.2 *HV Channel Model* 94
2.5.2.1 *Attenuation in HV Links* 96
2.5.3 *Noise in High Voltage Lines* 101
2.5.4 *Corona Noise* 103
2.6 MIMO Channels 104
2.6.1 *Grounding Methods* 106
2.6.2 *MIMO PLC Principles* 106
2.6.3 *Experimental Measurement Results* 108
2.6.3.1 *Equipment: MIMO Couplers* 108
2.6.3.2 *Statistical Channel Characterization* 109
2.6.4 *Modeling and Generation of MIMO PLC Channels* 114
2.6.4.1 *Top-down Modeling Approach* 114
2.6.4.2 *Bottom-up Modeling Approach* 118

2.6.5 *Beyond the Channel Frequency Response* 121
2.6.5.1 *Line Impedance* 121
2.6.5.2 *EMC Related Aspects* 123
2.6.5.3 *MIMO Background Noise* 123
2.7 Noise and Interference 124
2.7.1 *PLC Noise Analysis* 125
2.7.1.1 *PLC Noise in Time Domain* 126
2.7.1.2 *PLC Noise in Frequency Domain* 127
2.7.1.3 *PLC Noise in the Spectro-temporal Domain* 130
2.7.1.4 *Overall Noise Waveform* 132
2.7.2 *Statistical-physical Modeling of PLC Noise* 132
2.7.2.1 *Gaussian Mixture and Middleton's Class-A: Model Description* 134
2.7.2.2 *Gaussian Mixture and Middleton's Class-A: Model Derivation* 135
2.7.2.3 *Resulting Statistical Models* 136
2.7.3 *Empirical Modeling of PLC Noise* 137
2.7.3.1 *Time Domain Approach for Impulsive Noise* 137
2.7.3.2 *Frequency Domain Approach* 138
2.7.3.3 *Periodic and Cyclostationary Noise Model* 138
2.7.4 *PLC Noise Features for Adaptive Coding Modulation and Demodulation* 140
2.8 Reference Channel Models and Software 142
2.9 Channels in Other Scenarios 143
2.9.1 *Low Voltage Direct Current (LVDC) Distribution System* 143
2.9.1.1 *Structure and Characteristics of an LVDC Distribution System* 144
2.9.1.2 *PLC in the LVDC Distribution System* 147
2.9.1.3 *PLC Channel Characteristics in the LVDC System* 147
2.9.2 *In-car Power Line Communication Channels* 154
2.9.2.1 *Configuration of an Automotive Wiring Harness* 154
2.9.2.2 *Channel Transfer Function* 156
2.9.2.3 *Input Impedance of the Electrical Circuit* 158
2.9.2.4 *Noise and Interferences* 159
2.9.3 *Power Line Communications On-board Ships* 161
2.9.3.1 *In-ship PLC Literature Review and Power Grid Peculiarities* 161
2.9.3.2 *Grid Topology and Measurements On-board a Mega-yacht* 162
2.9.3.3 *Sensitivity of the Transfer Function to the Node Admittance* 164
2.9.3.4 *Variation of the Node Admittance and Identification of the Big Nodes* 166
2.9.4 *Final Remarks* 167
References 167

3 Electromagnetic Compatibility **178**
H. Hirsch, M. Koch, N. Weling, and A. Zeddam

3.1 Introduction 178

3.2 Parameters for EMC Considerations 179
3.2.1 EMC Relevant Transmission Line Parameters 179
3.2.2 Coupling Factor 182
3.2.3 Electric and Magnetic Field 183
3.3 Electromagnetic Emission 185
3.3.1 Radiated Emissions 186
3.3.2 Conducted Emissions 188
3.4 Electromagnetic Susceptibility 190
3.5 EMC Coordination 191
3.5.1 Compatibility Level 191
3.5.2 Definition of Limits 192
3.5.3 Cognitive Radio Techniques 193
3.6 EMC Standardization and Regulation in Europe 197
3.6.1 Distinction Between Standardization and Regulation in the EU 198
3.6.2 EMC Regulation for PLC 199
3.6.2.1 Market Access 199
3.6.2.2 Regulation in the Case of Interference Complaints 200
3.6.3 EMC Standardization for PLC 201
3.6.3.1 CENELEC 201
3.6.3.2 ETSI-CENELEC Joint Working Group 203
3.6.3.3 International EMC Product Standardization 204
3.7 Coupling Between Power Line and other Wireline Communications Systems 206
3.7.1 Characterization of the Coupling Between Power Line and Telecommunications Line Inside the Home Environment 206
3.7.2 Influence of the PLC Transmission on the Delivery of Services over VDSL2 208
3.7.2.1 Laboratory Tests 208
3.7.2.2 Field Test Measurements 216
3.7.3 Influence of a VDSL2 Transmission on PLC 217
3.7.4 Summary and Ways to Mitigate Impacts 219
3.8 Final Remarks 220
References 221

4 Coupling **223**
C. J. Kikkert

4.1 Introduction 223
4.2 Coupling Networks 227
4.2.1 Requirements 227
4.2.2 Capacitive Coupling 230
4.2.3 Inductive Coupling 232
4.2.4 Real RF Transformers 233
4.2.5 Resistive Shunt 236
4.2.6 Inductive Shunt 237
4.2.7 Modem TX and RX Impedances 240
4.2.8 Transformer Bypass Coupling 242

4.2.9 *Reactive Power and Voltage and Current Ratings* 246
4.2.10 *Uncertainties* 246
4.2.11 *Summary* 247
4.3 LV Coupling 247
4.3.1 *Introduction* 247
4.3.2 *N-PLC Couplers* 248
4.3.3 *B-PLC Couplers* 249
4.3.3.1 *Impedance Matching* 250
4.3.4 *Phase-to-phase Coupling* 252
4.3.5 *Single Phase Coupling* 252
4.4 HV Coupling 252
4.5 MV Coupling 257
4.6 Summary 258
References 258

5 Digital Transmission Techniques 261
K. Dostert, M. Girotto, L. Lampe, R. Raheli, D. Rieken, T. G. Swart, A. M. Tonello, A. J. H. Vinck, and S. Weiss

5.1 Introduction 261
5.2 Single Carrier Modulation 262
5.2.1 *Frequency Shift Keying* 262
5.2.2 *Spread Spectrum Modulation* 270
5.2.2.1 *Types of SS Technologies: Direct Sequencing Spread Spectrum (DSSS)* 270
5.2.2.2 *Types of SS Technologies: Frequency Hopping (FH)* 277
5.2.2.3 *Types of SS Technologies: Chirp* 282
5.2.2.4 *Evaluation of Benefits and Drawbacks SS Technologies for PLC* 285
5.2.2.5 *Practical Applications of SS Technologies in PLC Systems* 286
5.3 Multicarrier Modulations 287
5.3.1 *Multicarrier Modulation as a Filter Bank* 288
5.3.2 *DFT Filter Bank Modulation Solutions* 290
5.3.2.1 *Efficient Realization* 290
5.3.2.2 *Filtered Multitone Modulation (FMT)* 292
5.3.2.3 *Orthogonal Frequency Division Multiplexing (OFDM)* 294
5.3.2.4 *Pulse-Shaped OFDM and Windowed OFDM at the Transmitter* 296
5.3.2.5 *Windowed OFDM at the Receiver* 298
5.3.2.6 *Offset-QAM OFDM* 299
5.3.3 *DCT Filter Bank Modulation Solutions* 300
5.3.3.1 *Discrete Wavelet Multitone (DWMT)* 300
5.3.3.2 *DCT-OFDM* 300
5.3.4 *Other MC Schemes* 301
5.3.4.1 *Cyclic Block Filtered Multitone Modulation* 302
5.3.5 *Coexistence and Notching* 304
5.3.6 *Bit Loading* 305