Second Edition

# Power Line Communications

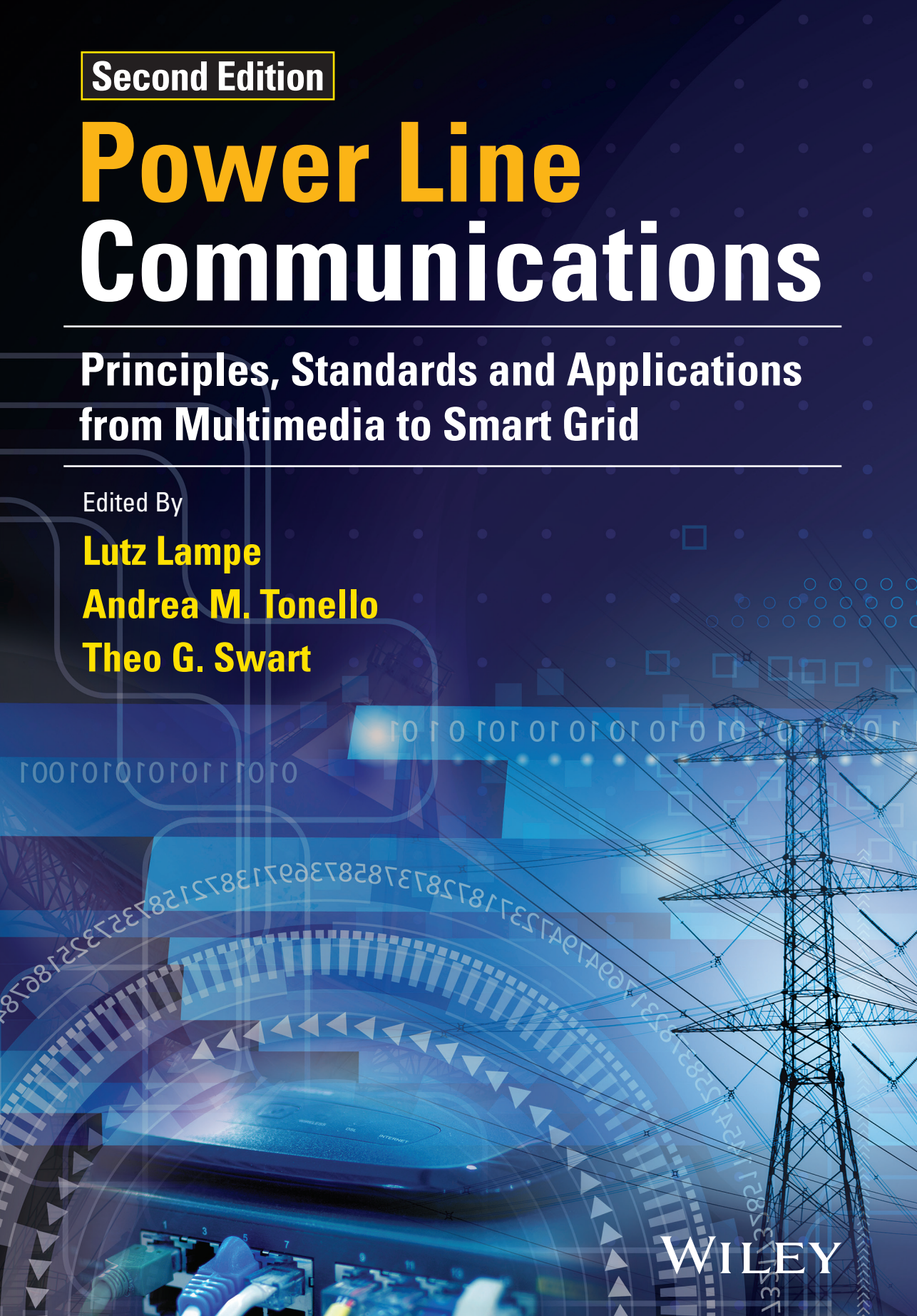
## Principles, Standards and Applications from Multimedia to Smart Grid

Edited By

Lutz Lampe

Andrea M. Tonello

Theo G. Swart



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## PRINCIPLES, STANDARDS AND 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

1 2016

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# 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 |

# 1

# Introduction

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

Power line communications (PLC) reuse existing infrastructures (i.e. power lines) whose primary purpose is the delivery of AC (50 Hz or 60 Hz) or DC electric power, for the purpose of data communications. Hence, compared to the electric power 'signal', PLC uses high-frequency signals with frequency components starting from a few hundred Hz up to a few hundred MHz. The plurality of frequency bands used for PLC is related to different applications supported by PLC and their data-rate requirements, the specifics of grid topologies over which PLC is applied, as well as the ability of PLC technology to deal with the harsh communication environment. Before elaborating on this further, we first briefly review the terminology that has been used to describe PLC.

## 1.1 What is a Name?

Communication over power lines is referred to by different names that are often specific to the considered grid domain and application. The most commonly used terminologies are summarized in the following.

- Carrier-current systems: This term refers to the fact that carrier-modulated data signals are transmitted over power lines. It has often been used to collectively describe relatively narrowband signals with frequencies below 500 kHz. The Code of Federal Regulations, Title 47, Part 15, from the U.S. Federal Communications Commission (FCC) [1] defines carrier-current systems as 'A system, or part of a system, that transmits radio frequency energy by conduction over the electric power lines.'
- Power line carrier: Similar to carrier-current systems, this is an early terminology used for systems that transmit carrier-modulated signals over power lines. A prominent example of its use is the 'Guide to Application and Treatment of Channels for Power-Line Carrier' by the 'AIEE Committee on Carrier Current' of the American Institute of Electrical Engineers

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(AIEE) [2], see also [3]. Also due to is earlier use, it typically refers to systems operating at frequencies below 500 kHz.

- Distribution line carrier (DLC): DLC refers to power line communication systems serving applications in the distribution domain. Due to the many line discontinuities and branches in the distribution grid, DLC systems face a more difficult communication environment than power line communication systems operating in the transmission segment of the power grid. DLC usually describes systems using frequencies below 500 kHz.
- Broadband over power lines (BPL): BPL is a more recent terminology that refers to systems operating in the frequency range of about 2 MHz to 30 MHz and beyond, with a signal bandwidth of tens of MHz and with data rates ranging from several Mbps to hundreds of Mbps; hence the term 'broadband'. The application of BPL systems is mainly in the distribution part of the grid, to enable broadband access, as well as for in-home communication. 'BPL' is mostly used in North America. For example, the Subpart G of [1] is entitled 'Access Broadband Over Power Line (Access BPL)'.
- Power line telecommunications (PLT): This term is used similar to BPL, but it is more popular in European countries. For example, the European Telecommunication Standards Institute (ETSI) produced numerous reports and specifications on 'PLT' through its 'ETSI Technical Committee Power-Line Telecommunications (PLT).'

In this book, we understand and use the term 'power line communications (PLC)' as including all of the above, which has been widely accepted by now. For example, the leading scientific conference on the topic is the 'International Symposium on Power Line Communications and Its Applications (ISPLC)' [4], and the IEEE Communications Society has established the 'Technical Committee on Power Line Communications (TC-PLC)' [5]. To differentiate the various PLC technologies, reference [6] introduced a classification of PLC into ultra-narrowband (UNB) PLC, low data rate narrowband (LDR NB) PLC, high data rate narrowband (HDR NB) PLC and broadband (BB) PLC. We will discuss this further in the context of the historical development of PLC in the next section.

## 1.2 Historical Notes

Figure 1.1 illustrates the evolution of the PLC technology by identifying some early patents, specific application domains and international standards along a timeline.

The origins of PLC can be traced back to the late 1800s and again in the early 1990s. Patents [11] and [12] consider remote meter reading via PLC (see [13]). The first description of remote load management using PLC, or so-called ripple control, is given in [14] (we note that [15] mentions the slightly earlier patent submission [16]). These ripple control systems (RCS) were developed further in the 1930s [17] and at a larger scale in the 1950s [18] to establish unidirectional communication for load management and other control functions in the power distribution grid. RCS use high-power and narrowband PLC signals. The signal frequencies are between 125 Hz and 3 kHz so that signals can pass through the distribution transformers and reach consumers. Before the widespread use of PLC via ripple control in the distribution domain, power line voice communication over medium-voltage and high-voltage transmission lines became popular in the 1920s [19]. These systems operate in the frequency