

**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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# 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 <i>or</i> Connection Manager

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CP	Cyclic Prefix <i>or</i> 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 <i>or</i> 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

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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 <i>or</i> 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

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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

(AIEE) [2], see also [3]. Also due to its 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