IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Digital Object Identifier 10.1109/ACCESS.2019.2942516

EDITORIAL

IEEE ACCESS SPECIAL SECTION EDITORIAL: ADVANCES IN POWER LINE COMMUNICATION AND ITS APPLICATIONS

Power line communication (PLC) is a growing technology which utilizes the existing pre-installed power delivery infrastructure for data transmission. While it is true that the history of PLC technology goes back to the beginning of the last century, when the first data transmission over power lines took place for low data rate control and monitoring purposes, PLC has recently regained a considerable amount of research attention due to the dawn of the internet and the increasing need for fast connectivity. PLC is also expected to serve as a reliable communication medium for many emerging applications of Internet of Things (IoT) and Smart Grids (SGs).

PLC has a number of advantages that make it an appealing complement, as well as a competitor, to other wireless technologies. For instance, PLC does not require any new wiring installations, which can significantly reduce the deployment costs. Another advantage of this technology is its ability to communicate with hard-to-reach nodes where RF wireless signals suffer from high levels of attenuation, similar to the underground structures, buildings with obstructions and metal walls, or simply when the wireless signal is undesirable for Electromagnetic interference issues, such as in hospitals. Furthermore, PLC can provide a low-cost solution to complement other existing technologies such as RF wireless or visible light communication systems. In particular, SG is one of the most important applications of PLC. Although the realization of SG can be achieved using several communication solutions, PLC remains the most popular and attractive candidate because of the widely available infrastructure as well as the fact that PLC is a through-the-grid technology, which reduces the reliance of utility companies on third-party connectivity. Other applications that can also benefit from PLC include smart city, telemetry, home and industrial automation, etc.

The goal of this Special Section is to provide insights and views into the developments in the area of PLC and its applications, as well as to provide directions for research in this field. This Special Section has attracted many submissions contributed by academic and industrial researchers to identify and discuss technical challenges and recent results related to PLCs. After an extensive peer review processes, we have selected nine high-quality articles for final publication, briefly summarized below.

The work presented in the article "The role of power line communications in the smart grid revisited: applications, challenges, and research initiatives," by Lopez *et al.*, provides an interesting update on PLC technologies and their applications in the context of SGs, the main challenges they are currently facing, how they can be addressed, as well as the current research initiatives.

Huo *et al.*, in the article "Cable diagnostics with power line modems for smart grid monitoring," propose a technique that harnesses power line modems (PLMs) for monitoring cable health. They envisage that all or most of these PLMs have already been deployed for data communication purposes and focus on the distribution grid or neighborhood area networks in the SG. For such a setting, the authors propose a machine learning (ML)-based framework for automatic cable diagnostics by continuously monitoring the cable status to identify, assess and locate possible degradations. As part of this technique, they also synthesize the state-of-the-art reflectometry methods within the PLMs to extract beneficial features for the effective performance of the proposed ML solution. The findings presented in this study demonstrate the effectiveness of the proposed solution under different aging conditions and varying load configurations.

The article by Tonello *et al.*, "Machine learning tips and tricks for power line communications," provides a vision of what ML can do in PLC systems. This article starts with a brief description of classical formulations of ML, distinguishing deterministic from statistical learning models with relevance to communications. The authors then proceed with discussing ML applications in PLC for each layer: characterization and modeling, development of physical layer algorithms, media access control and networking. Furthermore, other PLC applications that can benefit from the usage of ML, such as grid diagnostics, are also analyzed. The presented results provid encouraging evidence that ML has a role to play in future PLCs.

Ahiadormey *et al.*, in the article "Performance analysis of two-way relaying in cooperative power line communications," present a detailed mathematical framework for half-duplex TWR PLC systems in log-normal fading in terms of average capacity and outage probability. The performance analysis of one-way relaying (OWR) PLC systems are also studied for the sake of comparison. The authors considered two common relaying protocols, namely, amplify-and-forward (AF) and decode-and-forward (DF). A performance comparison between the OWR and TWR systems shows that the latter considerably improves the average capacity; thus, the spectral efficiency loss incurred by the former approach is effectively compensated for with the latter. However, the outage probability of the TWR PLC system is inferior to that of the OWR. Furthermore, in order to enhance the performance of the considered systems, the authors implemented a hybrid PLC/wireless approach. The impact of impulsive noise is also studied and results show its impact on the system performance.

Llano *et al.*, the authors of "Impact of channel disturbances on current narrowband power line communications and lessons to be learnt for the future technologies," analyze the impact of the PLC channel disturbances on the performance of the physical layer of the three main narrowband PLC technologies approved by international communication organisms and currently deployed in Europe: PoweRline Intelligent Metering Evolution (PRIME) 1.3.6, PRIME 1.4 and G3-PLC. This work develops a replicable, fully automated, and cost-optimized test scenario, based on an innovative Virtual PLC Laboratory, which provides a replicable and automated test process, where a wide range of channel disturbances can be accurately replicated, and the performance of the PLC technologies can be compared under the same conditions. The authors presented interesting results and drew important conclusions which can be very useful for developers when designing future PLC technologies.

In the article, "Real-time impedance estimation for power line communication," Liang *et al.*, propose a new technique to track the line impedance by only the channel frequency response (CFR). The relationship between CFR and impedance behavior is studied in detail, and it is shown that the variations in certain key factors, such as the frequency characteristics and the values of peak-valley difference, of the CFR curves could be used to track the real-time impedance. Furthermore, the proposed impedance estimation algorithm harnesses the variational mode decomposition (VMD) as a feature extraction method to obtain useful frequency properties. A machine learning (ML)-based impedance model is also synthesized in the proposed approach. The authors examined the performance of the proposed impedance tracking method under different scenarios, and the obtained simulation results demonstrate the efficiencies of the formulated algorithms.

Fernandez *et al.*, in the article "Field trials for the empirical characterization of the low voltage grid access impedance from 35 kHz to 500 kHz," present results of field measurements of low voltage (LV) access impedance up to 500 kHz in different scenarios, with measurement locations close to end users and near transformers. The authors discuss results which provide useful information to analyze the characteristics of the LV access impedance, including variation with frequency, ranges of values for different frequency bands and analysis of specific phenomena. The findings in this work show a diverse frequency-dependent behavior of the access impedance in different scenarios, depending on the grid topology, the number of end users (that is, number and type of connected loads), and the type of transformation center. This article offers a better understanding of the transmission of narrow-band (NB)-PLC signals and electromagnetic compatibility (EMC)-related phenomena.

The article "Improving soft decoding by spectral leakage reduction in presence of narrow band interference in PLC," by Marrero *et al.*, addresses the estimation problem of the noise power spectral density (PSD) to perform soft-decoding. A general background noise (GBN) model and a narrowband interference (NBI) model are considered. The authors propose the use of the frame control (FC) symbol to reduce interference leakage on noise estimation and additionally investigate the use of payload symbols to further reduce spectral leakage. Results presented in this article reveal that considerable performance improvements can be attained with the deployment of FC-based estimation in soft-decoding procedures.

The article "Cyclic signals and systems in power line communications," by Cañete *et al.*, presents a comprehensive discussion on the characterization of PLC channels and their relevance to synchronization to the mains period. Theoretical results of the interplay between cyclostationary (CS) random signals and linear periodically time-varying (LPTV) systems for the particular case of sharing the same period are presented. The focus is on their application to PLC channels and what simplifies the general relations for LPTV filtering of random or deterministic signals that are rather complicated. The authors also present the implications of the slow variation character of actual PLC channels in the LPTV model while providing helpful approximations for the design of PLC systems. A review of the works devoted to the study of PLC channels' cyclic behavior is also provided, as well as a discussion on how current PLC technologies exploit the periodical characteristics, e.g. by means of adaptive modulation.

To conclude, the articles presented in this Special Section demonstrate the breadth and diversity of research in the field of PLC and its applications. We would like to thank all the authors for submitting their research work to this Special Section. We would also like to thank Margery Meyer and Dr. Bora Onat in the IEEE ACCESS Editorial Office for their massive support and help provided throughout the different stages of this Special Section. Last but not least, we really appreciate the contributions of many experts in the field who have kindly volunteered their time and participated in the review process providing constructive suggestions.

KHALED RABIE, ***Guest Editor***
Department of Engineering
Manchester Metropolitan University
Manchester M15 6BH, U.K.

ANDREA M. TONELLO, *Guest Editor*
Institute of Networked and Embedded Systems
Alpen-Adria-Universität Klagenfurt
9020 Klagenfurt, Austria

NAOFAL AL-DHAHIR, *Guest Editor*
Department of Electrical and Computer Engineering
The University of Texas at Dallas
Richardson, TX 75083-0688, USA

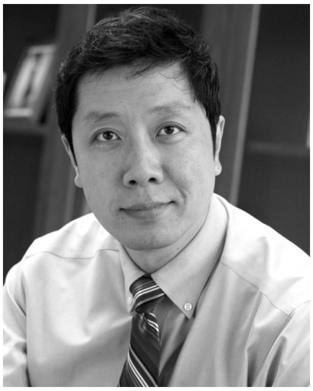
JIAN SONG, *Guest Editor*
Department of Electronic Engineering
Tsinghua University
Beijing 100084, China

ALBERTO SENDIN, *Guest Editor*
ICAI, ETSI
Universidad Pontificia Comillas
28015 Madrid, Spain

KHALED RABIE received the M.Sc. and Ph.D. degrees in electrical and electronic engineering from The University of Manchester, in 2011 and 2015, respectively. He is currently a Lecturer with the Department of Engineering, Manchester Metropolitan University (MMU), U.K. He has worked as a part of several large-scale industrial projects and has published over 90 articles in prestigious journals and international conferences (mostly IEEE). He serves regularly on the Technical Program Committee (TPC) of several major IEEE conferences, such as GLOBECOM, ICC, and VTC. He was a recipient of the Best Student Paper Award from the IEEE ISPLC, TX, USA, in 2015. He serves as an Associate Editor for IEEE ACCESS, an Area Editor for *Physical Communication*, and an Executive Editor for the *Transactions on Emerging Telecommunications Technologies* journal. He is also a Fellow of the U.K. Higher Education Academy (FHEA).

ANDREA M. TONELLO received the Dr.Ing. degree *(summa cum laude)* in electronics and the Dr.Res. degree in electronics and telecommunications from the University of Padua, Padua, Italy, in 1996 and 2002, respectively. From 1997 to 2002, he was a Member of Technical Staff with the Bell Labs-Lucent Technologies, Whippany, NJ, USA. Then, he was promoted as the Technical Manager and appointed as the Managing Director of the Italy Division, Bell Labs. In 2003, he joined the University of Udine, Udine, Italy, where he became an Aggregate Professor, in 2005, and an Associate Professor, in 2014. He is currently the Chair of the Embedded Communication Systems Group, University of Klagenfurt, Klagenfurt, Austria. He is also the Founder of a spin-off company WiTiKee. He was a recipient of several awards, including the Distinguished Visiting Fellowship from the Royal Academy of Engineering, U.K., in 2010, and the IEEE VTS Distinguished Lecturer Award (2011–2015), the Chair of Excellence from UC3M Madrid (2019–2020), the IEEE COMSOC Distinguished Lecturer Award, from 2018 to 2019, and nine best paper awards. He was the Chair of the IEEE Communications Society Technical Committee on Power Line Communications, from 2015 to 2018. He was also a Guest-Co-Editor of two special issues on PLC in the IEEE JSAC and the *IEEE Communication Magazine*. He was/is Associate Editor of the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, the IEEE TRANSACTIONS ON COMMUNICATIONS, IEEE ACCESS, and *IET Smart Grid*.

NAOFAL AL-DHAHIR received the Ph.D. degree in electrical engineering from Stanford University. From 1994 to 2003, he was a Principal Member of Technical Staff with the GE Research and AT & T Shannon Laboratory. He is currently an Erik Jonsson Distinguished Professor with The University of Texas at Dallas. He is the co-inventor of 42 issued U.S. patents. He has coauthored over 430 articles with over 11 000 citations. He was a co-recipient of four IEEE best paper awards, including the 2006 IEEE Donald G. Fink Award. He is the Editor-in-Chief of the IEEE TRANSACTIONS ON COMMUNICATIONS.



JIAN SONG received the B.Eng. and Ph.D. degrees in electrical engineering from Tsinghua University, Beijing, China, in 1990 and 1995, respectively. He was with the same university upon completing his graduation. He was also with The Chinese University of Hong Kong and the University of Waterloo, Canada, in 1996 and 1997, respectively. He has been with Hughes Network Systems, USA, for seven years before joining the faculty team in Tsinghua, in 2005, as a Professor. He is currently the Director of the Tsinghua's DTV Technology R&D Center. He has published more than 200 peer-reviewed journals and conference articles. He has been working in quite different areas with current research interests, including digital broadcasting and network convergence, wireless communications, and power line communications. He holds two U.S. and more than 50 Chinese patents. He is Fellow of the IET. He is also the Founding Editor-in-Chief of *ITU Journal: ICT Discoveries*.

ALBERTO SENDIN received the M.Sc. degree in telecommunication, the M.A. degree in management for business competitiveness (GECEM), and the Ph.D. degree from the University of the Basque Country, Spain, in 1996, 2001, and 2013, respectively. Since 1998, he has been with Iberdrola (one of the biggest electricity utilities) transforming its telecommunication network, Spain, where he is currently the Head of telecommunications. He is also a Professor with the University of Comillas ICAI, Spain, and the University of Deusto, Spain, with over two decades teaching telecommunications (main subjects are microwaves, radio communication systems, telecommunication systems, and projects and telecommunications for smart grids). He is the author of eight telecommunication books edited by McGraw-Hill, Artech House, and others, and tens of peer-reviewed papers. On PLC, he has contributed *Power Line Communications: Theory and Applications for Narrowband and Broadband Communications Over Power Lines*, *Power Line Communications: Principles, Standards and Applications from Multimedia to Smart Grid* (Second Edition), and *Communication and Networking in Smart Grids*.