Guest Editorial
Power Line Communications

DIGITAL communications over power lines is not a new idea, as several power utility companies have used power line communications (PLCs) for a couple of decades for narrowband applications such as metering and control. In the past few years, however, there has been a renewed interest in the possibility of exploiting power line cables as a *broadband* communications medium. Moreover, as opposed to the past, today's interest spans several important applications: broadband Internet access, indoor wired local area network (LAN) for residential and business premises, in-vehicle data communications, smart grid applications (advanced metering and control, peak shaving, mains monitoring), and other municipal applications, such as traffic lights and lighting control, security, etc. For some of these applications, products are already available on the market, allowing bit rates in the order of several tens of megabits per second (Mb/s). Additionally, industry specifications that allow data rates up to 200 Mb/s have been recently ratified, and the IEEE and the European Telecommunications Standards Institute (ETSI) have finally started working toward the standardization of PLC technology. On every continent, power utility and PLC companies are today partnering and carrying out field trials, some of which have also become commercial deployments with paying customers. In the past few years, many industry associations have also been formed, e.g. the HomePlug Alliance, the Universal Powerline Association (UPA), the Consumer Electronics Powerline Communication Alliance (CEPCA), the United Powerline Council (UPLC), etc.

The basic rationale for such enthusiasm is that the power grid provides an infrastructure that is much more extensive and pervasive than any other wired alternative, and that virtually every line-powered device can become the target of value-added services. Therefore, PLCs may be considered as the technological enabler of a plethora of future applications that would probably not be available otherwise. Despite all this recent enthusiasm, there is still some skepticism about the technology and its commercial viability. This skepticism is due to technical challenges, regulatory issues, and to the fact that today there is still no available standard. Among the main technical challenges of PLCs, we have: the power line channel is a very harsh and noisy transmission medium that is very difficult to model; the power line channel is frequency-selective, time-varying, and is impaired by colored background noise and impulsive noise; many transformers along the power line are fed by a single high-voltage line, with the earth itself being used for the return electrical path (a very noisy configuration for telecommunications signals); the structure of the grid differs from country to country and also within a country, and the same applies for indoor wiring practices; power line cables are often unshielded, thus becoming both sources and targets of electromagnetic interference (EMI); last but not least, regulations about electromagnetic compatibility (EMC) differ on a country-by-country basis.

To complicate things even further, the topic of PLCs lies at the intersection of several fields: circuit analysis, transmission line theory, electromagnetic theory, signal processing, and communications and information theory. It is certainly true that these considerations also apply to other (and more conventional) communications channels such as the wireless or the telephone channel, however, today, communications engineers have the availability of abstracted and simplified models for the wireless and telephone channels because the initial efforts devoted to the modeling of these classical channels date back many decades. Therefore, a shift from the electromagnetic and circuit analysis to the communication domain has naturally occurred with time. This is not yet true for the power line channel, whose modeling is still tied to approaches and tools of other-than-communications disciplines, so that adequate channel models have not yet been standardized, and there is no widely accepted channel model similar to those derived for mobile radio or telephone channels. The consequence of this is that a solid communications and information theoretic approach to PLCs is still lacking, and general results on the ultimate performance achievable over the power line channel are scarce. For the above reasons, we have devoted this special issue to communications-related problems, such as channel modeling issues and advanced modulation and coding techniques. We have not included the topic of EMI/EMC, i.e., coexistence between PLC systems and radio services in the high-frequency (HF) band, not because we do not think this is an issue of fundamental importance that deserves attention, but because we believe that an in-depth analysis of this issue would be better carried out and appreciated in a non-communications oriented journal.

We would like to point out that this is not only the first JOURNAL ON SELECTED AREAS IN COMMUNICATIONS (J-SAC) Special Issue on Power Line Communications, but also the first

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Special Issue on Power Line Communications ever made in an archival journal of the IEEE Communications, Information Theory, and Signal Processing Societies. It is interesting that most of the contributions on this topic are publications in the IEEE TRANSACTIONS ON CONSUMER ELECTRONICS, the IEEE TRANSACTIONS ON POWER DELIVERY, the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, AND the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, whereas very few papers on PLCs have appeared in publications traditionally dealing with communications problems. The purpose of this Special Issue is to bring together the work done by researchers in different areas with the goal of developing a better understanding not only of the practical issues related to PLCs but also of the theoretical ones, and to draw the attention of the communications, information theory, and signal processing communities to the interesting and challenging area of PLCs.

We have accepted 13 papers for this issue, selected among 52 submissions. We can divide the accepted papers into two main categories: Channel Modeling, and Communications and Signal Processing. Some of these papers contain results validated by measurements, and some do not. Although we believe that theory and practice should always go hand in hand, we also wanted to provide the readers with the latest analytical results on channel modeling and transceiver optimization.

A. Channel Modeling

We have six papers on the modeling of the outdoor and indoor power line channels, plus a paper that deals with a unique environment: communications over mass transit power traction networks. The issue of channel modeling is of paramount importance as any sensible communications system design needs to be matched to the particular characteristic of the channel. Due to the difficulty of modeling the power line channel, the first channel modeling attempts were mostly based on phenomenological considerations or statistical analysis derived from extensive measurement campaigns. More recently, papers attempting deterministic approaches have been appearing, thus indicating that a more basic understanding of the physical propagation of communications signals over power lines is now emerging. It is remarkable that the results of these deterministic approaches actually confirm the validity of some of the conjectures formulated during the time that analytical approaches were not deemed feasible, e.g., the multipath nature of signal propagation along power line cables. As the papers will confirm, the modeling of the power line channel is a challenging task that requires a truly interdisciplinary approach.

The first paper we present is, "A Mathematical Model of Noise in Narrowband Power Line Communication Systems," by Katayama *et al.* The noise on power lines is quite different from that of stationary additive white Gaussian noise (AWGN) channels. One of the most peculiar features of power lines is the presence of impulsive noise, and nonstationary background colored noise. This paper presents a mathematical model, validated by experimental results, capable of expressing the time-varying and colored features of the noise in power lines with only a small number of parameters.

The second paper is by Sartenaer and Delogne, and is entitled "Deterministic Modeling of the (Shielded) Outdoor Power Line Channel Based on the Multiconductor Transmission Line Equations." This paper proposes a "deterministic" approach to the modeling of the transfer function of the outdoor and underground power line cables based on multiconductor transmission line theory. A multidimensional scattering matrix formalism is also introduced to perform an accurate analysis of the global power line network, including multiconductor cable segments, derivation points, and termination loads.

The paper "High-Frequency Characteristics of Overhead Multiconductor Power Lines for Broadband Communications," by Amirshahi and Kavehrad, is the third paper in this issue. Similar to the previous one, this paper addresses the modeling of the transfer function of the outdoor power line channel advocating a deterministic approach based on multiconductor transmission line theory, but it focuses on the case of overhead power line cables. The authors exploit recent results on the modeling of dissipative transmission lines above lossy ground and conclude that previous models were not accurate at high frequencies since they did not incorporate ground admittance. On the basis of the proposed model, capacity values for a sample grid topology are given and it is also shown that previous models underestimated the potential of overhead lines as a medium for broadband communications.

Galli and Banwell authored the fourth paper, entitled "A Deterministic Frequency-Domain Model for the Indoor Power Line Transfer Function." The authors address the problem of modeling the indoor power line channel taking into consideration wiring and grounding practices. Crossing several layers of abstraction and following a bottom-up approach, it is shown that complex circuit-level models originating from multiconductor transmission theory can be manipulated and represented in terms of cascaded two-port networks, thus allowing one to compute *a priori* and in a deterministic fashion the transfer function of any power line link. The authors provide several experimental results to validate their analysis, and also propose a methodology for modeling both grounded and ungrounded power line links in a unified framework.

The fifth paper is, "Innovative Model for Time-Varying Power Line Communication Channel Response Evaluation," by Barmada *et al.* This paper addresses the important topic of characterizing the time-varying behavior of the power line transfer function due to the dynamic nature of the loads connected to the network. The channel is described by a two-port equivalent network represented by scattering matrices determined from a wavelet-based expansion of the input and output quantities. Upper and lower bounds for the response of the channel in the presence of time-varying loads are determined in a fast and efficient way avoiding time consuming Monte Carlo simulations.

The sixth paper on channel modeling is, "Analysis of the Cyclic Short-Term Variation of Indoor Power Line Channels," by Cañete and Cortés. This paper shows that the power line transfer function is time-varying even if the topology of the network and the loads attached to it do not undergo abrupt changes. It is, in fact, shown that the power line channel exhibits a short-term variation because the high-frequency parameters of electrical devices depend on the instantaneous amplitude of the mains voltage. This phenomenon leads to a channel model proposal based on a linear periodically time-varying system and cyclostationary random noise. Based on an extensive measurement campaign performed in several indoor power line scenarios, the authors provide a statistical analysis for evaluating the relevance of time variations in actual channels.

The seventh and last paper on modeling deals with an interesting application of PLCs and is entitled, "Mass Transit Power Traction Networks as Communication Channels," authored by Karols *et al.* The possibility of using PLCs for local traffic train automation is addressed here. To ensure efficient automatic train operation and safety in local transportation systems and mass transit systems, power traction networks can be used as a medium to support communication between wayside equipment and mobile equipment on moving trains. The authors analyze, on the basis of measurements, the properties of the multipath ultra-wideband and time-varying fading propagation channel that is typically found in mass transit systems.

B. Communications and Signal Processing

As stated several times in the modeling papers, the power line channel is truly a *horrible* channel, being a time-varying, frequency-selective channel characterized by both impulsive noise and non-Gaussian colored background noise. This poses serious challenges to the design of PLC modems and to the optimization of modulation and coding strategies. We have selected five papers that deal with the optimization of the physical-layer of PLC systems, and one paper on the analysis of the media access control scheme of HomePlug 1.0, an industry specification on which many commercially available PLC modems are based.

The eighth paper in our issue is, "A Simple Baseband Transmission Scheme for Power Line Channels," by Hormis *et al.* In this paper, the authors propose a simple pulse-amplitude modulation (PAM)-based coded modulation scheme that combines low-density parity-check codes, along with cyclic random-error and burst-error correction codes to achieve high spectral efficiency, low decoding complexity, and a high degree of immunity to impulse noise. To achieve good performance in the presence of intersymbol interference, the proposed coset-coding is combined with Tomlinson–Harashima precoding and spectral shaping at the transmitter.

The ninth paper is by Ribeiro *et al.*, and is entitled "An Interconnected Type-1 Fuzzy Algorithm for Impulse Noises Cancellation in Multicarrier-Based Power Line Communication Systems." The proposed algorithm exploits the ability of fuzzy systems to deal with uncertainties to reduce the presence of high-power impulse noises, while the discrete multitone/orthogonal frequency-division multiplexing (DMT/OFDM) technique copes with the severe intersymbol interference observed in power line channels. In particular, the authors propose an interconnected type-1 fuzzy algorithm which is trained by a modified version of the Scaled Conjugated Gradient method for impulse noises cancellation in DMT/OFDM-based systems for broadband PLCs.

The paper "Adaptive Spread Spectrum Multicarrier Multiple-Access Over Wirelines" is our tenth paper, and is authored by Crussière *et al.* The authors investigate dynamic resource allocation adapted to spread-spectrum multicarrier multiple-access (SS-MC-MA) systems in a multiuser PLC context. The developed adaptive system is valid for uplink and downlink, as well as for indoor and outdoor communications. The studied SS-MC-MA system is based on classical multicarrier modulation like DMT, combined with a spread-spectrum (SS) component used to multiplex several information symbols of a given user over the same subcarriers. A new bit-loading algorithm that dynamically handles the system configuration in order to maximize the data throughput is also proposed.

The topic of cooperative communications is very popular within wireless communications. However, also power line communications can benefit from cooperative schemes as described by Lampe *et al.* in the eleventh paper of this issue: "Distributed Space–Time Coding for Multihop Transmission in Power Line Communication Networks." Due to the broadcast nature of the power line channel, the authors argue that multiple repeater nodes may receive and retransmit the source message simultaneously. If no further signal processing is applied at the transmitter, simultaneous retransmission often deteriorates performance compared with single-node retransmission. Therefore, the authors advocate the application of distributed space–time block codes (DSTBCs) to the problem at hand and show that DSTBC-based retransmission does not require explicit collaboration among network nodes for multihop transmission and that detection complexity is not increased compared with single-node retransmission.

Another form of cooperative scheme is proposed in our twelfth paper, "Power Line Enhanced Cooperative Wireless Communications," authored by Kuhn *et al.* The authors investigate the use of PLCs to assist cooperative wireless relaying: the power line medium is used to initialize and synchronize wireless amplify-and-forward relays and to broadcast information between the relays. The proposed scheme is based on linear precoded OFDM, and it is designed to optimally exploit the frequency diversity available on power line channels. The interesting conclusion of the authors is that the use of PLCs leads to a very flexible way of enhancing wireless communications by plugging in additional relays where they are needed—without additional wiring.

Chung *et al.* author the thirteenth and last paper in our issue: "Performance Analysis of HomePlug 1.0 MAC With CSMA/CA." In this paper, the authors propose a new analytical model to evaluate the medium access control (MAC) throughput and delay of modems based on the HomePlug 1.0 specifications (the specifications of one of the few PLC modems available on the market today for home-networking) under both saturated and unsaturated traffic conditions. Although HomePlug 1.0 modems have undergone field trials and simulations, the analytical modeling of throughput performance of the MAC layer was only conducted for throughput under saturation conditions.

We want to express our thanks to the authors who submitted papers and to the reviewers for their diligent and timely efforts in assessing the quality and appropriateness of the submitted papers. We also want to express our gratitude to S. McDonald of J-SAC for her continuous and valuable help throughout the entire review and publication process.

It has been a pleasure to put this issue together, and we hope you enjoy it. We also hope that this Special Issue will become a valuable bibliographical resource to those starting to work on PLCs and who find themselves with the objective difficulty of dealing with a bibliography composed of technical papers scattered across a very large number of diverse journals. Finally, we also hope that this effort will provide researchers with the necessary tools for unveiling the ultimate performance achievable on the power line channel, as well as inspiring basic theoretical work that will lay the foundation for a new generation of communication technology for power line data transmission.

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Dr. Biglieri received the IEEE Third Millennium Medal and the IEEE Donald G. Fink Prize Paper Award in 2000, and the IEEE Communications Society Edwin Howard Armstrong Achievement Award in 2001. He was elected three times to the Board of Governors of the IEEE Information Theory Society, and served as its President in 1999. He has edited three books and coauthored six. He is a Distinguished Lecturer of the IEEE Information Theory Society and the IEEE Communications Society. He was an Editor of the IEEE TRANSACTIONS ON COMMUNICATIONS, the IEEE TRANSACTIONS ON INFORMATION THEORY, and the IEEE COMMUNICATIONS LETTERS, a Division Editor of the *Journal on Communications and Networks*, and the Editor-in-Chief of the *European Transactions on Telecommunications* and of the IEEE COMMUNICATIONS LETTERS.

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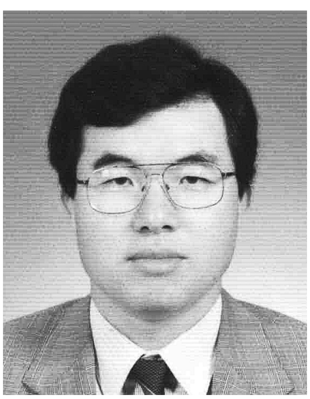
Dr. Galli is currently serving as Chair of the IEEE Communications Society Technical Committee on "Power Line Communications." He also served as a Co-Guest Editor for the Feature Topic "Broadband is Power: Internet Access through the Power Line Network" in the *IEEE Communications Magazine*, May 2003. He often serves as Technical Program Committee member in IEEE conferences, has served as the General Co-Chair of the IEEE Workshop on Signal Processing Advances in Wireless Communications (SPAWC'05), and is currently serving as the Vice-Chair of the General Symposium of the IEEE International Conference on Communications (ICC'06), and as the Co-Chair of the General Symposium of the IEEE Global Communications Conference (Globecom'06). He is also serving as an Associate Editor for the IEEE SIGNAL PROCESSING LETTERS and Area Editor for *Signal Processing for Communications*.



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From 1980 to 1985, he was with the Korea Agency for Defense Development as a Senior Engineer. From 1988 to 1994, he worked for Motorola Inc., where he was involved in the development of data transmission systems including high-speed modems. Since 1994, he has been with the School of Electrical Engineering, Seoul National University, where he is currently a Professor. He was Director of the Institute of New Media and Communications from 2001 to 2003 and Vice Chair of the School of Electrical Engineering, Seoul National University, from 2003 to 2005. His current research areas include the development of wireline/wireless transceivers, multi-antenna technology and robust signal processing for communications.

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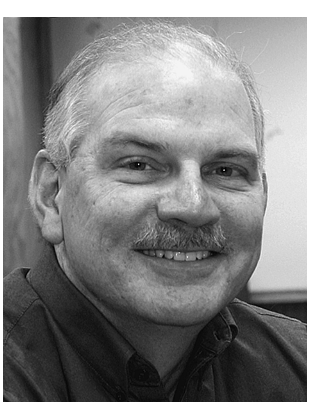

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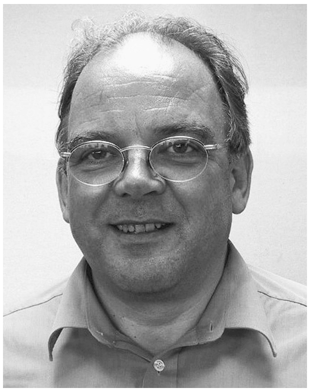
Dr. Poor is a member of the U.S. National Academy of Engineering and a Fellow of the American Academy of Arts and Sciences. He is also a Fellow of the Institute of Mathematical Statistics, the Optical Society of America, and other organizations. He is a past President of the IEEE Information Theory Society and the current Editor-in-Chief of the IEEE TRANSACTIONS ON INFORMATION THEORY. Recent recognition of his work includes the Joint Paper Award of the IEEE Communications and Information Theory Societies (2001), a Guggenheim Fellowship (2002–2003), and the IEEE Education Medal (2005).



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Dr. Vinck serves on the Board of Governors of the IEEE Information Theory Society since 1997 (until 2006). In 2003, he was elected President of the IEEE Information Theory Society. He served as Member-at-Large 2001–2002 in the Meetings and Services Committee for the IEEE. In 1999, he was the Program Chairman for the IEEE IT Workshop in Kruger Park, South Africa (175 participants). In 1997, he acted as Co-Chairman for the 1997 IEEE Information Theory Symposium, Ulm, Germany (704 participants). He was founding Chairman of the IEEE German Information Theory Chapter (1995–1998). In 1990, he organized the IEEE Information Theory Workshop, Veldhoven, The Netherlands (125 participants). The IEEE elected him as a Fellow for his "Contributions to Coding Techniques." He is the initiator of the Japan–Benelux Workshops on Information Theory (now Asia–Europe), and the International Winter-Meeting on Coding, Cryptography, and Information Theory. He started (Essen, 1997) and still supports the organization of the Series of Conferences on Power Line Communications and its Applications. He is Co-Founder and President of the Shannon and the Gauß Foundations. These foundations stimulate research and help young scientists in the field of information theory and digital communications. From 1999 to 2000, he was elected Chairman of the Benelux Information and Communication Theory Society.