Power Line Communications: State of the Art and Future Trends

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ABSTRACT

This article constitutes an overview of the research, application, and regulatory activities on power line communications. Transmission issues on the power line are investigated and modeling approaches illustrated. Contemporary communication techniques and reliability issues are treated. A brief description of regulatory activities worldwide is given. Finally, market perspectives and promising applications are covered to assess the viability of this communications environment.

INTRODUCTION

The usage of the power grid for control, maintenance, and charging purposes by the utility commodities has a long history [1–3]. The liberalization of telecommunications and the deregulation of electricity utilities have added new dimensions to the potential application of the electricity infrastructure for the most efficient use of the local loop. Furthermore, the birth and growth of the Internet accelerate the demand for digital telecommunications services to almost every premises. If such services can be carried over electricity distribution networks, a truly universal information superhighway might be realized, with the capability of providing interconnection to every home, factory, office, and organization.

Electrical distribution circuits constitute a universal wiring system, but they were not built for communication purposes. Varying levels of impedance and attenuation due to switching of electrical equipment are frequent. Time-variant interference from various sources leads to a very poor performance of the system. As a result the transmission capability is restricted resulting to severe bandwidth constraints, power limits, and high levels of noise.

In 1838 the first remote electricity supply metering and in 1897 [3] the first patent on power line signaling were proposed in the United Kingdom. In 1905 applications were patented in the United States, and in 1913 the first commercial production of electromechanical meter repeaters took place. By late 1980, relatively sophisticated error control coding techniques within the hardware of PLC modems were proposed. PLC standards have evolved constantly over the years, especially the last 20, and resulted after 1994 in the digital power line boost promising new revenues for energy utilities and cheap Internet access for consumers.

Medium voltage lines used as backbones for telecom operators have become a mature technology. Clearly the main focus is and will continue to be on the connection between house and transformer as a solution for the "last dirty mile" problem. Furthermore, new interest arises due to recent developments regarding in-house networking. However, to develop these applications in a commercially attractive way seems to still be hard for various reasons.

Essentially, what is missing is a clear regulatory framework. In Europe the CENELEC band (3–148.5 kHz) is currently allocated to classic narrowband applications, with a maximum signal power of 5 mW and rates up to 144 kb/s over distances around 500 m. However, today these applications seem very conservative, and research has focused on transmission frequencies via power lines above 1 MHz. Power line telecommunications (PLT) systems are demanded for data rates of several megabits per second. These systems operate over low voltage electricity distribution networks (LVEDNs) and are capable of providing commercially attractive broadband digital access solutions.

The need to harmonize broadband wireline access technologies with existing radio services so that coexistence might be optimized will be a key element in the rapid deployment of broadband PLT systems. The subject of EMC and broadband power line communications (PLC) applications, which propose to utilize sections of the high frequency bands, are now the focus of much detailed research (www.plcforum.org) [1].

The main issues encountered in such research are treated in brief in the following paragraphs. Academic and industrial activities are covered thoroughly, illustrating the open

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topics for discussion and further interpretation. Then channel modeling and measurement techniques are given, followed by communication techniques. The hot topic of regulation is covered, and finally, market status and perspectives are investigated.

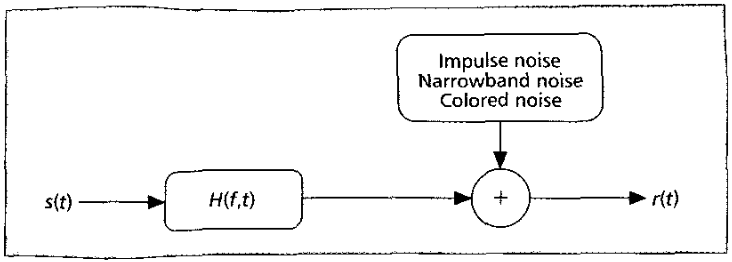


Figure 1. *Communication model of a powerline channel.*

THE CHANNEL

CHANNEL CHARACTERISTICS

Power lines constitute a rather hostile medium for data transmission. Varying impedance, considerable noise, and high attenuation are the main issues. The channel mixes the nasty behavior of a power line with that of a communication channel. The transmission environment for PLC seems much worse than that for mobile communications, so we need to not only utilize existing advanced technologies, but also create novel ones.

Channel characteristics can be both time- and frequency-dependent, and also dependent on the location of transmitter and receiver in the specific power line infrastructure. Hence, the channel can in general be described as random time varying with a frequency-dependent signal-to-noise ratio (SNR) over the communication bandwidth. Generally, a measured in-house (10 m) transfer function shows some deep narrowband notches spread over the whole frequency range. Phase angles decrease with frequency, and at amplitude notches we note phase nonlinearities (Fig. 1).

Quite a few measurements in the frequency and time domains for high-bit-rate transmission have been reported, converging essentially to some general conclusions (Fig. 2).

Impedance is highly varying with frequency and ranges between a few ohms and a few kilo-ohms with peaks at some frequencies where the network behaves like a parallel resonant circuit. In most frequency ranges the impedance shows inductive or capacitive behavior around 90 Ω to 100 Ω. The net impedance is strongly influenced by the network topology and connected loads, so we can say that the low voltage mains do not have essentially characteristic impedance since loads being switched on and off randomly introduce a change in impedance [1].

Measurements in houses for frequencies of 5–30 MHz in both European appliances as well as in the U.S. infrastructure resulted in some general and common conclusions for the absolute value |Z| of the impedance:

- The magnitude |Z| increases with frequency in the range of 5–20 MHz.
- It shows strong fluctuation between a maximum and a minimum value.
- Its mean value increases from ~5 Ω at 20 kHz to ~120 Ω at 30 MHz
- There are no big differences between the mean values of impedance presented throughout the 30 kHz–1 MHz spectrum range; whereas throughout 1–30 MHz they are almost uniform.
- The European impedance values do not vary significantly from country to country.
- Resonances can occur in residential networks, usually above 40 kHz. They make the impedance at higher frequencies more unpredictable than that at the frequency range of 5–20 kHz.
- Of various loads, resistive heating loads cause the greatest residential impedance changes for lower frequencies.

Carrying out impedance measurements outside buildings from 9 to 95 kHz, we find that the residential power circuit has extremely low impedance in most cases. The impedance varies with time and location. A maximum value that was measured was 4 Ω at 9 kHz at the rural location, and a minimum value was 0.4 Ω at 40 kHz at the suburban location. These low values are attributed to "the large capacitor that is used for power factor correction at 50 Hz that represents a short circuit in 9–95 kHz range reducing even lower overall impedance values" [4]. Mea-

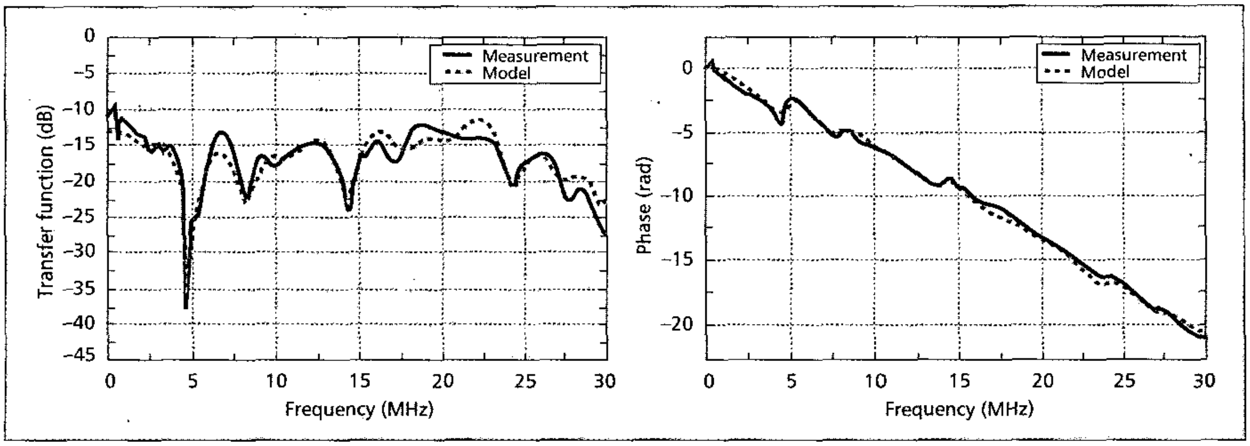


Figure 2. *Transfer function and phase characteristics of measurements and echo model by Holger Philipps [1].*

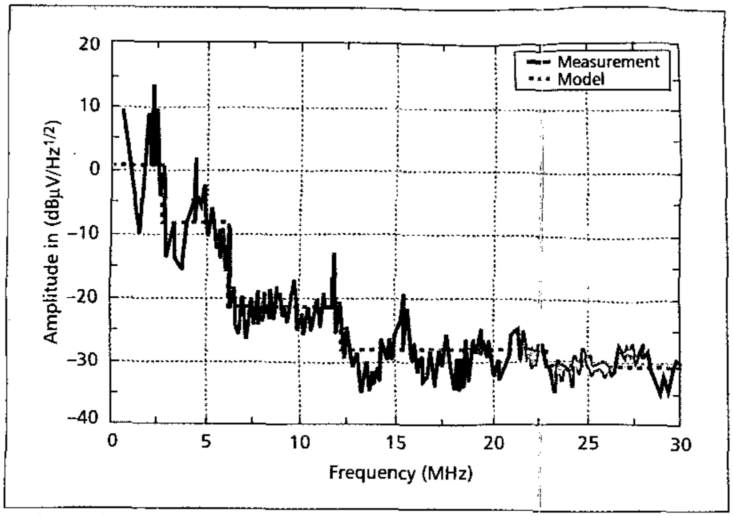


Figure 3. *Noise distribution measurement and modeling by Holger Philipps [1].*

surements and models for the frequency range of 500 kHz–20 MHz can be found in [1, 5].

Characteristic indoor and outdoor records of *attenuation* have been reported in the literature. Measurements have been made at a voltage of 0.35 V rms on in-house lines, resulting in about 15 dB attenuation, and on a 1 km cable feeding a cluster of houses, resulting in 50 dB attenuation. In the range of frequency of 9–95 kHz the line losses ranged between 40–100 dB/km depending on the location where the attenuation was measured [4].

So far research has focused on LVEDNs, but some studies on medium voltage cables (10–30 kV) were reported in [1]. A large variety of cables exist differing in general structure, number of cores, conductor material, and insulation used.

NOISE

Communication signals at low frequency are propagated along the low voltage power line through conducted emission with very little energy radiated from the line causing interference to other communication services. Different noise sources, motors, radio signals, and power supplies result in a noise curve very much dependent on location and time. Generally, channel noise varies strongly with frequency, load, time of day, and geographical location. Figure 3 depicts typical noise distribution and modeling.

The noise spectrum in the frequency range up to 145 kHz consists of four types of noise [4, 6, 7]:

- Colored background noise, which is the summation of low power sources like universal motors. Its power spectral density is frequency-dependent and decreases for increasing frequencies.
- Periodic impulse noise (synchronous and asynchronous to the power frequency) stemming from appliances that produce harmonics of 50 or 100 Hz.
- Narrowband noise consisting of sinusoidal signals with modulated amplitudes (radio stations, the horizontal retrace frequency for television, etc.).
- Asynchronous impulsive noise (noise bursts of switching operations).

In [1], attenuation as well as impulse and background noise measurements are reported. The noise power level ranges according to the distance between the noise source and receiver, and in most cases was found to be below –40 dB (W/kHz). Significant noise sources are universal motors to frequencies up to 50 kHz. It is worth mentioning that, since noise as well as wanted signals are subject to attenuation, noise sources close to the receiver will have the greatest effect on the received noise structure, particularly when the network attenuation is large.

MODELING AND SIMULATION TOOLS

For efficient communications a thorough understanding of the power line channel described with as few parameters as possible is required. The modeling approach is generally based on the transfer function and additive noise studies. The received signal is often modeled as the sum of a filtered version of the transmitted and interfering signals. These characteristics are dependent on frequency, time, and location of the transmitter and receiver in a specific power line infrastructure. Measurements show that channel characteristics do not change very quickly, and coherence time is large compared to typical symbol duration; hence, the channel model is quasi-stationary.

There are several approaches to modeling the transfer characteristics of power lines that we can classify in two categories:

- The *hardware* approach, based on impedance of the cables and network topology.
- The *communication* approach, where the channel is modeled by its attenuation, phase shift or noise sources, insertion losses, and so on.

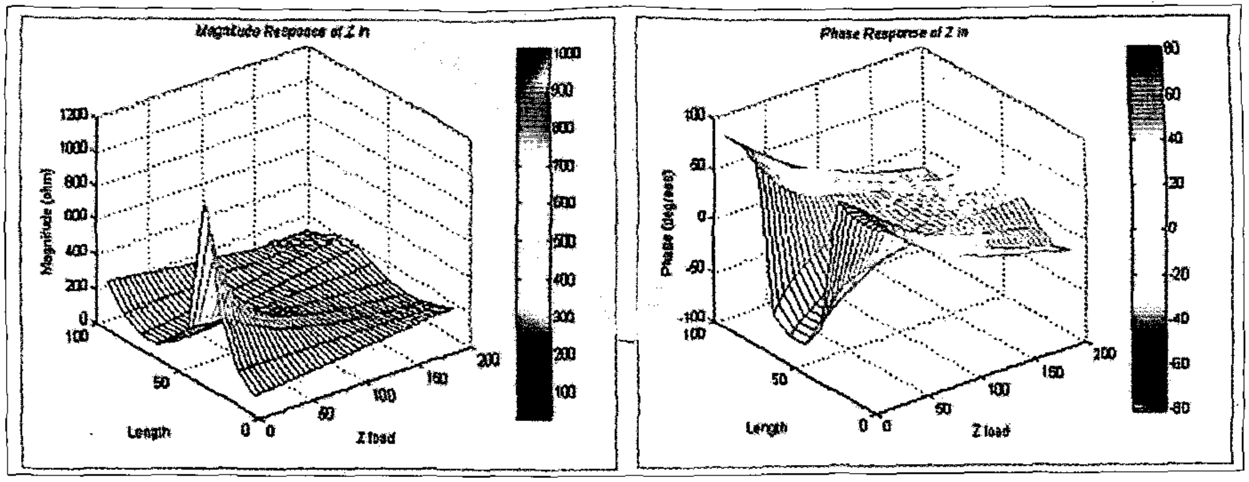
This model permits us to use classical communication methodologies and tools to estimate expected performance [1, 5].

Some modeling tools have been developed based on transmission line theory using a mathematical approach, while others are based on physical measurements of the nodes. Figure 4 shows a single load's magnitude frequency and phase response using PLAT, *Power Line Analyzing Tool* [8], which is one such mathematical approach used to measure the characteristic impedance of the power line channel in a multinodal situation.

COMMUNICATIONS TECHNIQUES

MODULATION TECHNIQUES

Generally, different modulation schemes such as frequency shift keying (FSK), code-division multiple access (CDMA), and orthogonal frequency-division multiplexing (OFDM) are discussed as appropriate choices for PLC [9]. Depending on the target application, each modulation technique has certain advantages. For a lowest-cost and low-data-rate power line system FSK seems to be a good solution. For higher data rates up to 1Mb/s CDMA offers the advantage of using



■ **Figure 4.** *Single load frequency and amplitude response [7].*

the system's inherent processing gain to meet radiation allowance limits. For FSK a significant part of the spectrum is attenuated more than 40 dB (3–6 MHz range). There are also parts that are not flat for FSK transmission. Transmission rates up to 10 Mb/s can be achieved with more band-efficient modulation techniques such as OFDM.

The exploitation of electric power distribution networks appears under completely new aspects when *spread spectrum* (SS) techniques are involved. Spread spectrum, due to its robustness against interference and its ability for multiple access operation, has been considered as a solution for PLC. Around 1985 several Japanese manufacturing companies as well as the Japanese Post Office Ministry worked enthusiastically toward planning a power line home bus system. The first proposal using SS was put forward by NEC in 1983. NEC Home Electronics Co., Ltd. developed a SS power line home communication system at a 10–450 kHz frequency band and a bit rate of 9.6 kb/s, with a processing gain of 31. Some work on phase hopping has also been reported, but an essential drawback is that the resulting spectrum is continuous [10].

In SS systems a cost-effective solution of the synchronization problem is of decisive importance. The power line network provides a voltage with relatively high stability of frequency and moderate corruption by interference. The zero crossings of the voltage represent basic synchronization reference instants [9]. Some basic attempts at synchronization error analysis in mains-borne systems have been made. Adaptive cross-correlation cancellers have been proposed to suppress co-channel interference [10].

Recently OFDM and discrete multitone (DMT) have been proposed as very good candidates for transmission due to their merits in simplifying channel estimation, and high bandwidth efficiency and flexibility in high bit rates. The total bandwidth is divided into N parallel subchannels, and bits are assigned to subchannels in direct proportion to the subchannel SNRs. The scheme that assigns the energy and bits to the different subchannels is called a *loading algorithm*. OFDM has proven its ability to deal with multipath propagation in wireless broadband transmission systems as well as with radio interference in asymmetrical digital subscriber line. Due to the very low transmit power permitted and the high attenuation expected, only a very low SNR is present at the receiver input. Hence, channel coding is unavoidable.

CODING

In the low frequency range below 150 kHz, a combination of M-ary FSK modulation and coding can provide a constant envelope modulation signal, frequency spreading to avoid bad parts of the frequency spectrum, and time spreading to facilitate correction of frequency disturbances and impulse noise simultaneously. A transmission scheme (in agreement with the existing CENELEC norms) combining M-ary FSK modulation with diversity and coding can make transmission over power lines robust against permanent frequency disturbances and impulse noise. It can be considered a form of coded frequency hopping and is easy extendable to any frequency range.

Coded OFDM schemes with combined adaptive modulation have been proposed recently. Furthermore, space time coding is a new coding/modulation technique for multiple-antenna wireless systems. Simulation results demonstrate that significant gains are achieved over the use of single-input single-output (SISO) systems [11].

MEDIUM ACCESS CONTROL ISSUES

Generally, most medium access control (MAC) techniques are candidates for this communications environment: fixed access, dynamic protocols with contention, arbitration protocols (token, polling), and reservation protocols. Power grid networks usually form a bus or tree topology (Fig. 5), where in the latter case the medium/low voltage (MV/LV) transformer is located at the root of the tree. Communication between any pair of terminals is possible; however, most traffic is expected to be from and to a terminal serving as the network gateway and is usually placed on the MV/LV transformer.

Polling and *Aloha* are two of the most stud-

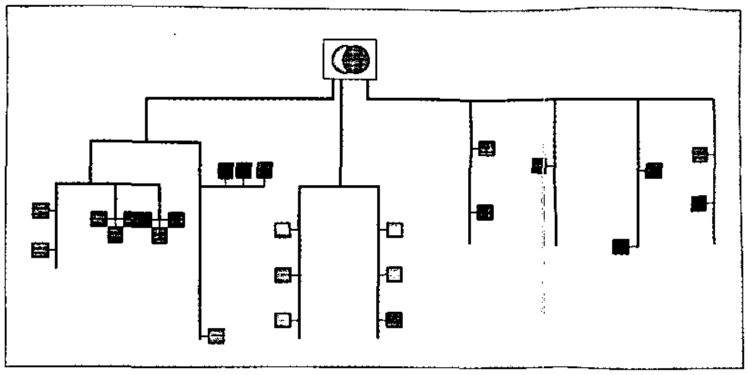


Figure 5. *A PLC distribution network.*

ied protocols for medium access. The main disadvantage of Aloha is the low throughput as the offered load increases, as well as its lack of support for quality of service. On the contrary, polling can handle heavy traffic and inherently provides quality of service guarantees. However, polling can be inefficient under light or highly asymmetric traffic patterns or when polling lists must be updated frequently as network terminals are added or removed. Similarly, token passing schemes (token ring, token bus) are efficient under heavy symmetric loads, but can be expensive to implement and serious problems could arise with lost tokens on noisy unreliable media such as the power grid used in PLC.

Carrier sense multiple access (CSMA) is also proposed with overload detection. CSMA is efficient under light to medium traffic loads and for many low-duty-cycle bursty terminals (i.e., Internet browsing). The primary advantage of CSMA is its low implementation cost, since it is the dominant technique in today's wired data networks. Collision detection (CSMA/CD) could enhance the performance of CSMA, but on power line networks the wide variation of the received signal and noise levels makes collision detection difficult and unreliable. An alternative to collision detection that can be easily employed in cases of PLC is collision avoidance (CSMA/CA), a technique that uses random backoffs to further reduce the collision probability. The Bluetooth protocol is another choice, and of course proposals on time-division multiple access (TDMA) are found in the literature. Generally a detailed treatment of the protocol stack is still needed [12–14].

In parallel, well-known *error handling mechanisms* can be applied to solve the problem of errors, but the use of these mechanisms consumes part of the transmission capacity and decreases the already limited data rate of PLC systems. Application of automatic repeat request (ARQ) and hybrid schemes can avoid the influence of short-term disturbances, while dynamic strategies for capacity allocation can successfully confront long-term disturbances [15] (Fig. 6).

Furthermore, power line networks present a number of *security* challenges due to their open insecure bus structure. Two services that are necessary for those networks are confidentiality and identity authentication.

STANDARDS AND REGULATORY ISSUES

One of the major issues currently under debate is the radiation emission of power lines. Sources of emission from powerlines networks can be the upstream signals at customer premises, the upstream signals at adjacent customer premises, and downstream signals at the substation.

For mains-borne communications, there is a European standard, EN50065-1:1991 [16]. This standard actually regularizes PLC but only in a small frequency band (see introduction). Outside International Telecommunication Union (ITU) Region 1 (Europe) there is IEC61000-3-8 for up to 525 kHz. Also, concrete detector structures are considered for the analysis.

Above 150 kHz, EN50065-1 specifies much lower limits that are the same as the Class B limits in the EN55022 standard for ITE and the generic emission standard EN50081-1. Similarly, above 525 kHz in ITU Regions 2 and 3, the relevant electromagnetic compatibility (EMC) standards for mains communications systems specify conducted emission limits that are the same as for equipment such as ITE. In both cases, the limits are small compared to the levels of signal injection, which would normally be required for a practical mains-borne communication system, particularly if communication is required outside the confines of a single building.

Efforts are going on in the United States through the Electronics Industry Association (EIA), IEEE, and Automatic Meter Reading Association (AMRA) Committee SCC31, and in Europe via CENELEC, to develop new EMC standards for PLC systems from 2 MHz up to 30 MHz. It is doubtful whether practical PLC systems can operate under the EN55022 regime because of the trade-off between interference and performance.

A CENELEC/European Telecommunications Standards Institute (ETSI) joint working group has been set up to develop EMC requirements for transmission networks (power line, coaxial, telephone). This group is dealing with the intended single general EMC emission standard. This standard covers emission limits and measurement methods for all types of telecommunication networks to ensure that the various technologies are treated equally.

MARKET PERSPECTIVES/APPLICATIONS

The PLC market is expanding dynamically (www.plcforum.org). Some applications are reported in the ISPLC conferences [1]. Advanced energy services include applications such as automatic meter reading, programmable controllers, and demand/supply management. Traditionally, this application area has been pushed by energy companies and related manufacturers. Permanent connection via PLC offers utility companies a possibility to get real-time information that may be of strategic relevance, especially by creating differentiation concepts in the liberalized energy markets. Numerous products enabling advanced energy services are already commercially available, especially due to the fact that the required data rates can be realized within the current frequency allocation (CENELEC band).

Electricité de France (EDF) has used PLC for a long time for management and their own transmission network, in energy control, street lighting, and remote service (a large project with 3600 terminals). Around 1998 the Tokyo Electronic Power Company (TEPCO) was involved in several projects linking consumers and utilities for meter reading and lowering peak loads.

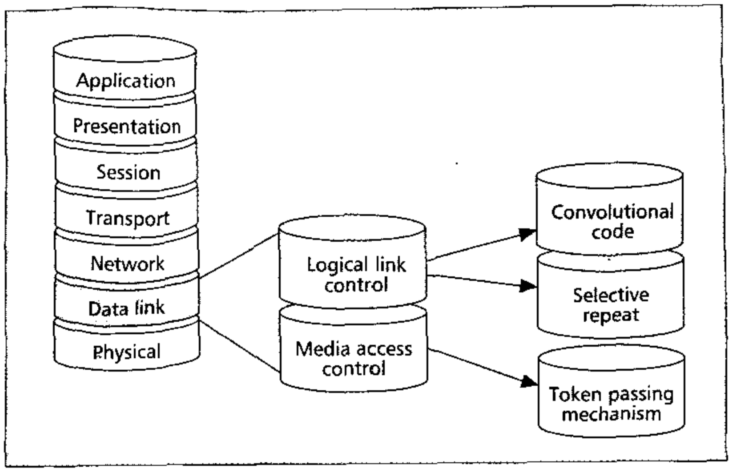
PLC networking *in the home* is another application area serving two goals: providing a local home network with the advantages of the power line, and combining access and in-home network capabilities for service and system integration. There are several applications for a PLC network in the home: shared Internet, printers, files, home control, games, distributed video, remote monitoring/security. The key asset is "no new wires." Available products are in net-connected security, safety, and convenience service systems using narrowband communications.

In the United States, home networking is becoming a mass market (10 percent over PLC). In the beginning of 2000 the HomePlug Powerline Alliance, Cogency, Conexant, Enikia, Intellon, Netgear, RadioShack Co., Sharp, and Texas Instruments, together with several other major companies as participants and adopters (http://homeplug.com), began work toward a common standard in the United States. The HomePlug Powerline Alliance is a non-profit corporation formed to provide a forum for the creation of open specifications for high-speed home power line networking products and services. Adopters of the HomePlug 1.0 standard have developed products for in-home networking reaching 14 Mb/s.

The European Home System (EHS) consortium [www.ehsa.com] defines a bus and communication protocol for communications between appliances and a central processing unit in the home. The EHS specification, EHS 1.3, covers several medium types to transport control data, power,and information, all sharing the logical link control (LLC) sublayer. At the moment, the best supported medium types are power line carrier (230 Vac + data, 2.4 kb/s, CSMA/ack, topology-free) and low-speed twisted pair (15 Vdc, 48 kb/s, CSMA/CA, topology-free).

In parallel, some EU projects have covered the topic, such as INSONET (http://www.cordis.lu/ist/projects/99-10358.htm), Palas (http://palas.regiocom.net), and 6POWER (http://www.6power.net); they are proof of the existing interest in this field.

Design of Systems on Silicon (DS2) is the lead partner in the European Commission supported R&D project Mixed Analog Digital Broadband Integrated Circuits (MADBRIC). The consortium includes Cisco, Electricité de France, and the Switzerland Institute of Technology, Zurich (ETH-Z). Their products can achieve speeds up to 45 Mb/s. They have recently announced a next generation of 200 Mb/s PLC technology products.



■ **Figure 6.** *The data link layer of the OSI model used for power line protocol.*

Even if the technology works for some time, the biggest question remains unanswered: can services built on this technology compete in price (and quality) with services already offered by digital subscriber line or cable? The technology probably has a future in remote areas served by power cables that cable and telecom operators find too expensive to connect to their broadband services [17].

CONCLUSIONS

The power line communication field still constitutes an open and attractive research area. Many studies are still necessary to better understand and improve the performance of power lines for high-bit-rate transmission. So far measurements, modeling, and transmission techniques have been the first priority in the activities of the investigators in the area, but now a stimulus in enhanced performance, coding, and MAC protocols and applications is noticed.

Finally, the most crucial issues remain the treatment of emissions of high-frequency signals through the line and the standardization procedures.

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BIOGRAPHIES

FOTINI-NIOVI PAVLIDOU [SM] (niovi@vergina.eng.auth.gr) received a Ph.D. degree in electrical engineering from the Aristotle University of Thessaloniki, Greece, in 1988 and a Diploma in mechanical-electrical engineering in 1979 from the same institution. She is currently with the Department of Electrical and Computer Engineering of the above institution engaged in teaching and research on mobile communications and telecommunications networks. Her research interests include traffic analysis and design of networks, performance evaluation and QoS studies of mobile communications, multimedia applications over the Internet, and multicarrier communications techniques. She is involved in European projects (Telematics, COST Actions, Tempus, IST) as well as national projects in the referred scientific areas. She has served on the Program Committees (as a member or chairperson) of many conferences and workshops supported by IEEE/IEE including the 6th International Symposium on Power Line Communications and Its Applications in 2002. She was the chairperson of the COST 262 Action on Spread Spectrum Applications for Wireless and Wired Communications and is currently the delegate of Greece in the COST program. She has published about 80 technical papers in journals or conferences. She was the guest editor of a Special Issue on Ad Hoc Networks for the *International Journal for Wireless Information Networks*. She is Chairperson of the Joint VT and AES Chapter in Greece, and a member of the Technical Chamber of Greece.

A. J. HAN VINCK (vinck@exp-math.uni-essen.de) is a full professor in digital communications at the University of Essen, Germany, since 1990. He studied electrical engineering at the University of Eindhoven, The Netherlands, where he obtained his Ph.D. in 1980. His interest is in information and communication theory, and coding and network aspects in digital communications. From 1991 to 1993 and 1998 to 2000 he was the director of the Institute for Experimental Mathematics in Essen. He was the director (1997–1999) of the Post-Graduate School on Networking, CINEMA. In 2000 he became the chairman of the communication division of the Institute for Critical Infrastructures (CRIS). He 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. In 1999 he was the Program Chairman for the IEEE IT Workshop in Kruger Park, South Africa. In 1997 he acted as Co-Chair of the 1997 IEEE Information Theory Symposium in Ulm, Germany (704 participants). He was founding Chairman (1995–1998) of the IEEE German Information Theory chapter. In 1990 he organized the IEEE Information Theory Workshop in Veldhoven, the Netherlands. 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, 19 97) 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 Gauß Foundations. These foundations stimulate research and help young scientists in the fields of information theory and digital communications. From 1999 to2000 he was chairman of the Benelux Information and Communication Theory Society.

JAVAD YAZDANI (j.yazdani@lancs.ac.uk) graduated with his B.Eng. and M.Eng. Hons degrees in mechatronics engineering in 1991. He was also awarded an M.Sc. in digital signal processing and a Ph.D. in high-frequency digital power line transmission for terrestrial and marine networks from Lancaster University in 1996 and 2002, respectively. His major area of research is focused on the transmission of multimedia information reliably across the power line infrastructure of marine vessels. This also includes the design and development of protocols specific to point-to-multipoint PLT networking. His current research activities include the application of space-time diversity and coding to power line communication channels to optimize channel throughput. This focuses on the investigation of multiple conductors and implementation of smart modem technology based on PLT multiconductor techniques with FPGA technology. He is now a postdoctoral research fellow in the Department of Communication Systems at Lancaster.

BAHRAM HONARY received his M.Sc. in digital communications and his Ph.D. in error protection techniques for bursty channels from the University of Kent at Canterbury in 1976 and 1982, respectively. He was also a lecturer at the University of Science and Technology, Tehran between 1976 and 1979. In 1984, after one year of postdoctoral studies at the University of York, he was appointed to a senior lectureship at Coventry University. In 1988 he joined the Department of Engineering, University of Warwick. In 1992 he took up a Chair in Communications Engineering at Lancaster University. Current research interests include channel coding and its application to radio communication channels, secure communication applications, modem design, and synchronization with over 300 publications attributed.His most recent book is *Trellis Decoding for Block Codes* (Kluwer, 1997). He is Chairman of the IEEE Chapter of Information Theory for the United Kingdom and the Republic of Ireland.