BROADBAND IS POWER: INTERNET ACCESS VIA POWER LINE NETWORKS

Broadband PLC Access Systems and Field Deployment in European Power Line Networks

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ABSTRACT

Data communications over low voltage power distribution networks provide an alternative and cost-effective last mile access technology. It offers data and voice services to users in residential and business areas. Currently, many field trials with different broadband power line communications systems are running worldwide. This article describes one of these systems for the last mile application in European power line networks. It addresses major field deployment aspects, such as range, coverage, coupling, and intercell interference.

INTRODUCTION

As an alternative last mile access technology, broadband power line communications (PLC) have been receiving tremendous interest in recent years [1]. Several PLC systems have been installed worldwide for various kinds of field trials. In particular, in Europe large-scale field deployment can be found, for example, in Germany, Spain, France, Austria, and Switzerland. Each country and area of the world poses unique challenges in the deployment. PLC access networks typically cover both the public area from the transformer substations to the customer premises (outdoor) and the private area within the customer buildings (indoor). The frequency spectrum available for communications is between 1 and 30 MHz. Within this spectrum the lower frequencies are preferably used for outdoor, the higher frequencies for indoor communications. Most of the systems available provide a maximum net data rate of more than several megabits per second.

This article describes in detail one PLC access system and the experience of its deployment in European power line networks. It provides insight into the typical PLC network architecture and system components, and addresses system design aspects related to power line channel characteristics and regulatory constraints. Details of the European low voltage power distribution network as well as important physical and regulatory constraints for PLC systems can be found in [2].

This article also deals with major field deployment aspects, such as range, coverage, coupling, and intercell interference. These aspects are not well documented in the scientific literature. In the following, several possible solutions are proposed, and their pros and cons presented.

NETWORK ARCHITECTURE AND SYSTEM COMPONENTS

To bridge the last mile between the transformer substation and the electrical outlets on the customer premises, it is necessary to divide the low voltage power distribution network into outdoor and indoor PLC segments. This is due to the typically very high attenuation of the complete path. Only about 10 percent of customers can be directly served by a one-hop link within the power constraints given by electromagnetic compatibility (EMC) requirements [2, 3]. As an example, Fig. 1 shows the network architecture and system components of a PLC system.

The outdoor segment covers the public area, which is from the transformer substation to the house access point (HAP), while the indoor segment refers to the private area, which is from the HAP to the electrical outlets inside a building.

The PLC system we implemented has a centralized master/slave architecture, which reflects the nature of the power line network topology and the point-to-multipoint flow of the network traffic. The outdoor master (OM), usually installed in the transformer substation, controls the outdoor access point (OAP) at the customer premises. An outdoor repeater (OR) is available to cover remote buildings.

In each served building, there is an independent indoor PLC governed by a so-called indoor controller (IC). The IC controls the indoor...
adapters (IAs), which provide standard network interfaces to the end users, such as Ethernet, USB, and analog phone line (a/b). The indoor and outdoor PLC are connected via an Ethernet link between the OAP and IC.

The OMs provide Ethernet interfaces for the backbone connection. Widely used technologies for backbone connection are fiber optic and digital subscriber line (DSL). For transformer substations without existing telecom infrastructure, medium voltage PLC can be used as an alternative solution.

The outdoor PLC uses the lower frequency band, 1–10 MHz, while the indoor PLC uses the higher frequency band, 15–30 MHz. Each band can accommodate up to three carriers, each with a bandwidth of about 2 MHz. The carrier frequency allocation is based on the following considerations:

- Coexistence with important incumbent broadcast and amateur radio services.
- Lower frequencies show less line attenuation and thus are more suitable for outdoors to achieve maximum distance.
- Sufficient separation between outdoor and indoor frequencies to enable simultaneous and uncoordinated operation of outdoor and indoor PLC systems in close proximity (e.g., in an OAP/IC).
- Indoor distances are typically shorter than outdoor distances. Thus, higher frequencies can be used indoors. Moreover, channel noise as produced by electrical appliances is much smaller at higher frequencies than at lower frequencies.
- Due to the better crosstalk characteristics between different phases at higher frequencies, the signal is present with nearly the same quality on each of the phases. Thus, the performance of the indoor system is less vulnerable to the particular phase or network branch by which an IA is served.

The PLC protocol contains physical (PHY), medium access control (MAC), and logical link control (LLC) layers, as well as a bridge function to the standard Ethernet data link control [4].

The PLC-PHY used is based on Gaussian minimum shift keying (GMSK) modulation [5]. It employs decision feedback equalization (DFE) to cope with multipath dispersion [6]. DFE is combined with a soft decision algorithm [7] to mask impulsive noise (for recent results on impulse noise measurements see [1]). Three different user data rates per carrier (750 kb/s, 1.1 Mb/s, 1.5 Mb/s) are available by changing the code rate of the applied convolution code. Code rate and carrier selection is adapted to the channel conditions in both link directions, downlink (master to slave) and uplink (slave to master), and individually for each master/slave link.

The design of the PLC-MAC is based on demand-driven dynamic frequency and time division (for PLC-MAC issues see [8]). On each carrier frequency, the time is divided into time frames, which are further divided into time slots. The master assigns transmit and receive carriers and time slots to the slaves once per time frame. Thus, the maximum aggregate throughput of 4.5 Mb/s is dynamically shared among active PLC users on a frame-to-frame basis.

Since the links operate in time-division duplex (TDD) mode, each frequency is used in both directions. This guarantees link symmetry in a transmission medium with highly frequency-dependent path attenuation.

The PLC-LLC provides a reliable and robust
packet transmission service to the Ethernet bridge. A selective automatic repeat request (ARQ) scheme is employed to recover corrupted LLC data blocks on the PLC link level. This dedicated error control scheme significantly reduces TCP/IP packet loss.

In this trial four different traffic priority classes are supported: voice, gold, silver, and best effort. In a heavily loaded system, traffic from a higher priority class will outperform traffic from a low priority class in terms of both throughput and delay.

**SECURITY AND PRIVACY**

Since the power line is a shared medium, it is very easy to access and monitor the data; therefore, encryption is required. In our field trial the encryption is performed using Rivest’s Cipher 4 (RC4) with the maximum possible key length of 128 bits, since it offers a good trade-off between encryption power and data processing requirements. The key exchange follows the Diffie-Hellman algorithm [9].

As each PLC node performs an Ethernet bridging function, the PLC system is equivalent to a LAN with a transparent Ethernet interface. To protect against unauthorized access between computers in the same PLC network, we included support for virtual LANs (VLANs) following the IEEE 802.1Q standard [10]. To allow the terminals to use a shared power line, we assign PLC nodes to different VLAN groups. PLC nodes belonging to the same user are assigned with the same VLAN identity number (VLAN ID). Each Ethernet frame entering the power line network is therefore tagged with a VLAN ID. PLC nodes will only bridge Ethernet frames with the same VLAN ID, while other frames will be dropped.

**RANGE AND COVERAGE**

Path loss and local noise are the predominant factors for the outdoor range [11]. The path loss depends on the cable type, cable length, coupling mismatch, number of branches, and number of street cabinets. Generally, the path loss grows with increasing frequency and distance. On the other hand, power line noise typically decreases with increasing frequency. The average noise power varies in the range between –65 and –80 dBm/MHz.

Coverage prediction is only possible in a probabilistic sense. Figure 2 shows a coverage prediction for the three individual outdoor carriers (2.4 MHz, 4.8 MHz, and 8.4 MHz). It is based on a path loss model derived from statistical data gathered in diverse outdoor networks in Europe. A log-linear distance law and log-normal distribution with a standard deviation of 12 dB is assumed.

According to this prediction, the probability of successfully connect a customer located at a cable distance of 200 m from the master station is higher than 90 percent when using the 2.4 MHz carrier. Taking into account that the path attenuation of the three carriers is partially correlated, it is estimated that a probability of coverage of 90 percent can be achieved at 250 m with at least one carrier. Outdoor repeaters (ORs) can be employed to reach longer distances. The OR shares the frequency resources over time with the OM. The OR can be installed, for example, in street cabinets. An OAP at the customer premises may take the repeater function in addition to its home gateway function.

Indoor coverage statistics usually show a modest dependence between path loss and distance. The line attenuation mainly depends on the number of subdistributions and branches along the signal path. A random model for the indoor attenuation can be a simple log-normal distribution with a mean and standard deviation specific to the building type. Our field experience shows that with a proper installation, as described below, more than 90 percent of electrical outlets can be covered indoors.

**INTERCELL INTERFERENCE**

In principle, adjacent PLC systems reusing frequencies may mutually interfere (intercell interference). In outdoor networks, this interference is mainly expected at the fringe of a cell and is caused by residual crosstalk at the cable ends (located in the street cabinets or in the link boxes). However, in our field trials outdoor intercell interference occurred rarely.

The predominant problem experienced is, instead, the interference between neighboring indoor PLC systems. In many cases, the attenuation via the outdoor path between adjacent ICs is similar or smaller than the indoor link attenuation. The interference between ICs can be minimized by intercell coordination of the usage of down- and uplink slots. In this concept, one IC is
defined as synchronization master of a group of potentially interfering ICs. This concept has been widely used in our field.

Another method adopted by us to substantially reduce intercell interference is coupling of the IC after the attenuating main distribution (meter panel), as described below.

**COUPLING AND INSTALLATION CONCEPTS**

In three-phase power line networks, phase-to-phase or phase-to-neutral coupling modes may be utilized. In the trial we have observed that phase-to-phase coupling in general performs better and causes less radiation.

Both inductive and capacitive coupling may be applied. Inductive coupling can be accomplished using high saturating magnetic toroidal half cores (e.g., Ferrite). A Ferrite core snapped on a wire of the power line acts as a single-turn high-frequency transformer. Inductive coupling should be used at places with low impedance (current maximum), while capacitive coupling is more suitable in places with high impedance (voltage maximum). The latter also allows to combine signal coupling with the modem power supply, requiring only a single connection to the power line.

Capacitive coupling is the preferred technique used at transformer substations if, in particular, the current ratings are above 200 A, the space is limited, and several feeders have to be served equally well.

For transformer substations with a small and compact distribution panel, a single-point coupling to the bus bar is an adequate solution. For older types of transformer substations with large distribution panels and many feeders (6 to 10), it is advantageous to apply a multiple-feeder coupling technique using a low loss power splitter/combiner (S/C) (Fig. 3a).

To serve a single family home, a joint capacitive coupling of the OAP and IC is the preferred solution because of its simplicity. In multi-apartment houses, multipoint inductive coupling is applied after the meter to bypass the house distribution system (Fig. 3b). In larger multistory buildings, it is common practice to connect the OAP and IC at the riser on a middle floor. This is a good trade-off between outdoor and indoor path attenuation since in residential areas with high population density the outdoor power line segment is typically shorter.

In general, selection of the appropriate coupling is crucial for the coverage. The right coupling may save 10–30 dB of path loss. Sometimes these gains must be paid for by increased installation effort.

**AN EXAMPLE OF FIELD DEPLOYMENT**

Table 1 shows statistics of a field deployment in a European power line network. It contains 153 outdoor and 342 indoor networks. On average one repeater is needed in every fourth outdoor network. For the connection of the OM signal, multiple-feeder capacitive coupling is usually applied. The OAP and IC are separately connected to the power line, as shown in Fig. 3b. In 10 percent of cases, coordination between neighboring indoor PLC systems is required to avoid interference.

**CONCLUSION**

This article deals with broadband PLC systems for the last mile access and their deployment aspects. As an example, one PLC system is described and the field trial experiences with this system are reported.

The high path attenuation and EMC constraint requires a segmentation of the system into an outdoor and an indoor PLC system. The lower frequencies, in the range of 1–10 MHz, are preferably used for the outdoor PLC, whereas the higher frequencies in the range of 15–30 MHz are more suited for indoor PLC. The time-division multiple access/TDD technique is expected to be a good choice because of the highly frequency selective channels; it also enables optimum usage of the bandwidth for bursty and asymmetric data traffic. In the field trials the maximum outdoor distance achieved without a
Table 1. Statistics of a field deployment in an European power line network.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of OM s</td>
<td>153</td>
</tr>
<tr>
<td>Number of OAPs/ICs</td>
<td>342</td>
</tr>
<tr>
<td>Number of IAs</td>
<td>841</td>
</tr>
<tr>
<td>Number of repeaters</td>
<td>40</td>
</tr>
<tr>
<td>Percentage of apartment buildings</td>
<td>80 percent</td>
</tr>
<tr>
<td>Percentage of single family houses</td>
<td>20 percent</td>
</tr>
<tr>
<td>Max. distance to remote PLC user</td>
<td>450 m</td>
</tr>
<tr>
<td>Coupling of OM signal</td>
<td>Multiple-feeder capacitive coupling</td>
</tr>
<tr>
<td>Coupling of OAP/IC signal</td>
<td>Separated (IC: inductive; OAP: capacitive)</td>
</tr>
<tr>
<td>Backbone connectivity</td>
<td>Fiber optic mainly</td>
</tr>
</tbody>
</table>

repeater is about 250–300 m, which covers most customers served by a transformer substation in rural and urban areas of Europe. Longer distances require a repeater at the expense of bandwidth efficiency.

The trial experience showed that the interference between adjacent indoor PLC systems is a major issue of concern and that the synchronization of the down- and uplink slots between interfering PLC systems effectively minimizes this problem.

Finally, the trial experience also showed that proper signal coupling is essential to achieve good coverage. Multiple-feeder coupling is a powerful means to avoid huge attenuation caused by large distribution panels at transformer substations or in the basement of customer premises. Depending on the impedance at the coupling point, maximum current rating, and available space, either capacitive or inductive coupling can be used to connect PLC nodes to the power line.

Among others, future development shall focus in particular on the following areas:

- **Bandwidth**: The future PLC access system will have to deliver higher data rates.
- **Coupling**: The coupling concept has to be further unified and simplified to facilitate large-scale rollout.
- **Intercell interference cancellation**: With a large rollout of PLC nodes, intercell interference will occur more frequently. Hence, the future PLC access system shall incorporate built-in interference avoidance and/or an automatic interference detection and mitigation concept.

### References


### Biographies

Weilin Liu (weilin.liu@ascom.ch) received a Dipl.-Ing. degree from the Technical University of Munich in 1986 and a Dr.-Ing. degree from the University of the Federal Armed Forces, Munich, in 1990, both in electrical engineering. He joined the Ascom group in 1991 as a research engineer and worked on system/algorithm design and evaluation for various digital communications systems. Since 1997 he has been the project leader at Ascom to develop a broadband PLC access system.

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