

Evolution of powerline communications for smart distribution: From Ripple Control to OFDM

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Abstract—This paper describes the evolution of powerline communications for the control of power distribution grids. First generation ripple control systems provide one-way communication, with which centralized load control and peak shaving have been performed for many years. The European standards body CENELEC restricted the use of frequencies between 3 kHz and 95 kHz for two-way communications for electricity distributor use. A number of second generation PLC systems with low data rates were proposed in the 1990's, and Automatic Meter Reading systems have been deployed based on this technology. Third generation systems based on OFDM with much higher data rates are currently being developed and deployed for Smart Grids, Distribution Automation and Advanced Metering Management.

Keywords: *powerline, ripple control, smart grid applications*

I. INTRODUCTION

The electric power grid offers an obvious and compelling communications medium for its control. The power lines and cables can in principle carry telecommunication signals with total coverage. Powerline communications (PLC) have thus been employed since the beginning of active control of the power grid. On the high voltage (HV) wide area power transmission grid, the technology for long distance point-to-point HV-PLC links has developed continuously and is still widely used alongside non-PLC broadband wide area networks for SCADA communication [2]. On the medium and low voltage (MV and LV) distribution grids, however, technology and deployment of PLC has progressed in several phases, as will be described. This paper focuses on the narrowband PLC systems operated by European utilities for the control of the distribution grid and for automatic remote meter reading. There are also broadband over powerline (BPL) systems targeted for consumer Internet access and home network applications [3][20]. BPL maximizes data rate at the expense of communication range. For utility applications, coverage is more important than data rate, hence narrowband PLC with its potential to cover more difficult-to-reach locations is in general preferable to BPL. BPL systems are therefore not considered further here.

II. FIRST GENERATION: RIPPLE CONTROL

In the 1950's, Landis & Gyr, Brown Boveri [1] and a number of other companies developed ripple control systems for central load management in the electric power distribution grid, in particular to shave load peaks. Such systems have since been widely deployed and are still in daily use in many European countries [4][5] for load management and other operational functions, even for controlling switchgear, where there are no other telecontrol links.

In ripple control, an audio frequency signal is injected into the MV grid. Frequencies are chosen such as not to coincide with harmonics of the AC power (50 Hz, 60 Hz) and are typically in the range of 150 Hz to 1350 Hz. Lower frequencies below 250 Hz are preferred for large grids due to their lower attenuation. Adjacent distribution grid operators should use different frequencies to avoid interference. Injected signal level is up to about 5% of the AC power voltage level, corresponding to transmission outputs of 15 kVA to 150 kVA depending on the voltage level at the signal coupling point (Figure 1). The low frequency and the high power of the ripple control signal allow for wide area coverage. In particular, the signal easily passes through MV/LV transformers, so that one or few signal injection points in the MV grid suffices to reach all receivers connected to the LV grid of a typical distribution area over many kilometers. Transmission is uni-directional broadcast from the distribution grid operator only; however the system can be monitored by supervision receivers placed at selected locations, which return acknowledgement signals to the transmitter over separate communication links, such as copper wires.

Telegrams consist of a sequence of pulses of the carrier. Details vary [4], but typically bits are encoded as on/off pulses of several 100 ms duration, data rate is thus about 1 b/s. Telegrams carry commands of some 50 bits, and thus last several seconds to minutes. In the simplest case, the transmitted sequence is interpreted as a bit map of on/off commands broadcast over the entire coverage area. Receivers at the consumer side are configured to switch their electric relays on or off according to the received bits. More advanced systems combine area addressing with bit maps of commands, or encode commands as numbered codes. The receivers are then configured to recognize one or several codes and switch their

electric relays accordingly (where the relays are connected e.g. to the hot water boiler or electric room heating, Figure 2). New systems include error checking, fragmentation of long messages, and advanced functions, such as remote programming of timer functions in the receivers. While the principle of ripple control is common, the detailed designs are proprietary by the system suppliers. Only receiver type testing has been standardized [6].

Ripple control systems are routinely used for load peak shaving by distribution utilities: when total power consumption approaches a pre-set limit, groups of loads such as HVAC (electric heating, heat pumps, hot water boilers) or swimming pool pumps are switched off (for a configurable maximum duration), following a pre-programmed priority list. Also, time-based tariff high/low switching commands are broadcast to the meters by ripple control (Figure 2). Further commands concern the time-driven switching of groups of hot water boilers (e.g. every night, staggered to avoid peak artifacts), street lighting by area, and other large controllable loads.



Figure 1: Ripple control coupler (parallel capacitive coupler at 16 kV MV)

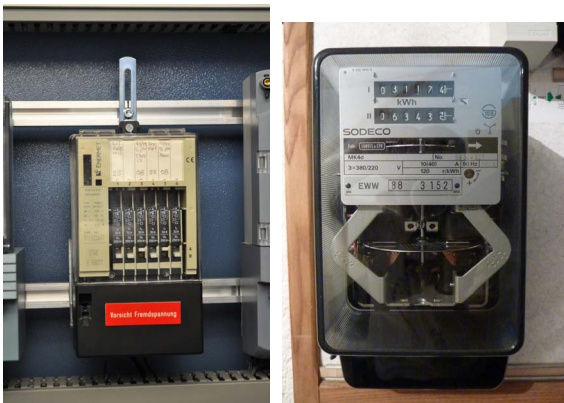


Figure 2: Ripple control receiver with electric relays (left), electromechanical meter with high/low tariff switched by ripple control (right)

III. SECOND GENERATION: TWO WAY COMMUNICATIONS

Distribution Automation (DA) applications, such as closed loop control and Automatic Meter Reading (AMR), require two-way communication with higher data rates than what ripple control systems can deliver. Thus there is a need for

more bandwidth at higher carrier frequencies, where also noise levels are typically lower [7][9]. High signal frequencies above some 10 kHz, and lower available transmit powers from consumer-side LV equipment imply, however, that signals will not easily pass through MV/LV transformers. This leads to a communication architecture consisting of a backbone network, possibly using MV-PLC, connecting gateways (concentrators) located at the MV/LV substation which provide LV-PLC communication over the last-mile to the customers attached to the given LV grid segment.

In 1991, CENELEC issued the European Norm EN 50065-1 [8] restricting frequency bands for MV/LV PLC:

- A Band: 3 – 95 kHz, for electricity distributors and their licensees.
- B Sub-band: 95 – 125 kHz, for consumer use without access protocol.
- C Sub-band: 125 – 140 kHz, for consumer use, with EN 50065-1 compliant CSMA access protocol.
- D Sub-band: 140 – 148.5 kHz, for consumer use without access protocol.

The CENELEC A-band is assigned to communications by electric utilities for DA and remote meter reading, while the remaining bands are intended for customers' on-site communications e.g. to home appliances. IEC 61334-3-1 [9] specifies output power levels of 1 W or 5 W and spectral masks for such PLC transmissions above 17.5 kHz.

Beginning in the 1980's, a number of two-way MV/LV PLC systems have been designed and realized in the CENELEC bands [7]. Some remained proprietary solutions, while some were also submitted to IEC for standardization [9][10]. Part 5-1 of [10] is Spread-Frequency Shift Keying (S-FSK) modulation by Landis & Gyr: two carriers at 63.3 kHz and 74 kHz are FSK modulated with a basic data rate of 300 b/s. The wide separation of the carrier frequencies allows diversity reception with improved performance in frequency-selective attenuation or noise: Receivers detect bits by either comparing the received two signal levels against each other, or by comparing one carrier level against a threshold if the other frequency is unusable. With a data rate of 1200 b/s, frames of 300 ms duration carry 45 bytes. Transmission range is 300 m to 500 m; for longer distances, several repeaters can be chained for multi-hop transmission. Many AMR networks based on S-FSK have been deployed, in particular in France, where ERDF plans to connect 35 million residential customers in the future.

Part 5-1 of [10] became an International Standard, while parts 5-2 to 5-5 have remained Technical Specifications. Part 5-2 of [10] is an FSK system by ENEL of Italy. A carrier at 82 kHz is FSK-modulated with a basic rate of 600 b/s, requiring a bandwidth of some 1200 Hz. A newer system achieves data rates of 2400 b/s. ENEL has been expanding its metering network for remote meter management and AMR since 2001 and has already reached some 30 million households.

Further physical layer profiles with different modulations have been submitted to [10]. Part 5-3 of [10] by Adaptive Networks specifies Direct Sequence Spread Spectrum Adaptive

Wideband (SS-AW) modulation for LV-PLC. Part 5-4 by ABB describes Multi-carrier Modulation (MCM) with differential PSK for MV-PLC (Figure 3), while Part 5-5, also by ABB, describes Spread Spectrum Fast Frequency Hopping (SS-FFH) for LV-PLC. However, these systems have not been deployed in any large installations.

The standard [9] includes other parts specifying the higher layers of distribution line communications. Section 4-41 of [9] contains the application protocol Distribution Line Messaging Specification (DLMS), while [11] is the Companion Specification for Energy Metering (COSEM) with the data models. The DLMS messaging separates the application layer COSEM data models from the underlying communication protocol. The DLMS/COSEM suite has thus become applicable for any communication protocol capable of carrying DLMS PDUs, such as PLC, telephone modems, or cellular data communications. DLMS/COSEM is supported by many advanced metering products.

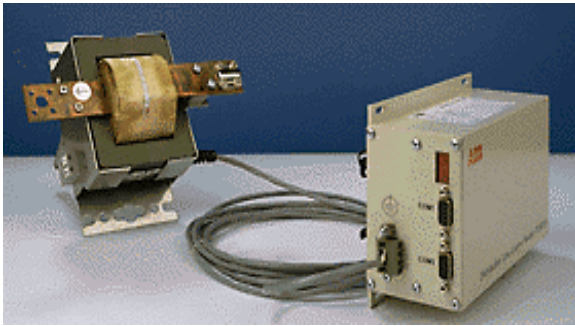


Figure 3: MV-PLC controller (IEC 61334-5-4) with MV inductive coupler

IV. THIRD GENERATION: HIGH DATA RATE OFDM

Real time Distribution Automation applications and advanced metering solutions require higher data rates than what second generation PLC systems can deliver. For a given noise level, higher data rates require the use of correspondingly larger bandwidths, e.g. as made available by the CENELEC A-band assignment of some 90 kHz. At such bandwidths, however, the frequency-selectivity of the channel transfer functions of LV- and MV- power lines becomes noticeable. The PLC signal modulation should therefore be chosen to allow easy channel equalization, or to be tolerant against distortion. Orthogonal Frequency Division Multiplexing (OFDM) is such a modulation format. A pioneer in employing OFDM for PLC was iAd, whose work became the basis of REMPLI, a system with speeds of up to 60 kb/s in the CENELEC bands [12].

OFDM [13] is a well-known approach which started to be used in modern systems in the 1990s [14]. It is currently used in xDSL technologies, terrestrial wireless distribution of television signals (DVB-T, DVB-H), and has also been adopted for IEEE's high rate wireless LAN Standards (802.11a and 802.11g). In less than twenty years OFDM has developed into a popular scheme for most of new telecoms standards: WiMAX, DAB, DRM, 3G cellular telephony, UWB, MoCA, IEEE P1901, etc.

OFDM is a digital multi-carrier modulation scheme, which uses a large number of closely-spaced orthogonal subcarriers to carry data. Subcarriers are PSK- or QAM-modulated and combined by an inverse Fast Fourier Transform (FFT) to form a long OFDM time domain symbol [15][16]. A short guard interval (cyclic prefix), covering the length of the channel impulse response, is inserted between the symbols. This prevents inter-symbol interference (ISI) in the time domain and ensures that the FFT-demodulated subcarriers at the receiver remain orthogonal despite the signal distortion, thus making OFDM easy to demodulate even in channels with high distortion. Equivalently, in the frequency domain, due to the small subcarrier spacing, the channel transfer function reduces to a simple constant *within the bandwidth of each subcarrier*. In this way, a frequency selective channel is divided into many flat fading subchannels, this eliminates the need for complex equalizers. Channel equalization is simplified because OFDM may be viewed as using many slowly-modulated narrowband signals rather than one rapidly-modulated wideband signal. Thus, the primary advantage of OFDM over single-carrier schemes is its ability to cope with severe channel conditions – for example, attenuation of high frequencies in long power lines, narrowband interference and frequency-selective distortion due to signal reflections in the power grid – without complex additional mechanisms.

A. PRIME

In recent years several initiatives have started to provide a worldwide PLC standard in the CENELEC band covering the lower layers (PHY and MAC) [12][17][18]. The focus has been on using new modulation techniques that could ensure that devices are prepared for new applications coming in the next years. As an evolution of Part 5-4 of [10], the application of OFDM to the CENELEC A-band was suggested by PRIME (PoweRline Intelligent Metering Evolution). PRIME was initiated in 2006 by the following companies: ADD Semiconductor, CURRENT Group, Iberdrola, Landis+Gyr, STMicroelectronics and ZIV Group. It is currently organized as the PRIME Alliance [17] and counts on 27 key industry members to evolve.

PRIME represents a joint collaborative effort to define standard PHY and MAC layers for an open, royalty-free PLC-based Smart Grid communication technology that looks for different vendors' equipment interoperability as a way to push for the growth of new metering markets. Three different types of industry players are present in the Alliance: meter manufacturers that bring their know-how in metering, telecom equipment providers that bring their expertise in PLC and communications, and semiconductor manufacturers that set up the limits of cost-effectiveness.

B. PLC G3

In response to a call by ERDF, Maxim and Sagem have developed the PLC G3 system for the CENELEC A-band, with a variant for the US FCC-allocated PLC bands (10 – 490 kHz). The PHY parameters of the CENELEC A-band variant are similar to the PRIME choices described below. The MAC layer is based on the MAC of the wireless IEEE 802.15.4 standard (CSMA and contention free periods). IPv6 is supported using

the IETF wireless 6LoWPAN mechanisms for segmentation and header compression.

C. IEEE P1901.2

In March 2010, working group IEEE P1901.2 was initiated to develop a standard for low frequency (less than 500 kHz) narrowband PLC for Smart Grid Applications on LV and MV grids. (A separate IEEE 1901 standard for BPL was approved in September 2010 [20].)

The standard will be based on PRIME and PLC G3, i.e. use OFDM in the 9 kHz to 500 kHz band. For the higher layers, support of IPv6 and RPL (IETF's 6LoWPAN's forthcoming Routing Protocol for Low power and lossy networks) is under discussion. An alternative option is to rely on link layer mechanisms.

D. ITU-T G.hnem

ITU-T working group G.hn began standardization efforts for broadband home networking back in 2008. In addition, ITU-T initiated in January 2010 a working group G.hnem "home networking aspects of energy management", to define a narrowband PLC standard for energy management applications, which is to be integrated to, and able to co-exist with, the broadband ITU-T G.hn PLC solution. It is expected that this work will be harmonized with IEEE P1901.2.

V. PRIME SYSTEM OVERVIEW

PRIME is currently considered to be the most mature example of a modern narrowband high data rate PLC system. This section gives an overview of this system and its status.

A. PRIME PHY

The PRIME OFDM format consists of OFDM symbols of 2.048 ms duration with a cyclic prefix of 192 μ s (corresponding to relative propagation path delays due to reflections in the grid of some 50 km). Modulation and demodulation are performed by 512-point FFTs, with a subcarrier spacing of 488 Hz. For actual data modulation, 97 subcarriers in the frequency band between 42 kHz and 89 kHz are used. Frequency-domain differential PSK modulation is employed, with multi-level differential phases between the subcarriers in the frequency domain, thus allowing simple equalizer-less demodulation. Achievable raw data rates are between 21.4 kb/s to 128.6 kb/s, depending on the adaptively selected number of phase levels (2, 4, or 8) and the error-correction coding (none or rate $\frac{1}{2}$). Telegram length depends on the payload length, maximum payload length are 63 OFDM symbols, so that maximum telegram duration is less than some 150 ms.

These modulation parameters were selected as a result from extensive field trials. In these trials it was found that:

- Lower parts of CENELEC A-band are unused due to its inherent unreliability and noise levels.
- Frequency domain differential PSK modulation was shown to be slightly superior to time domain differential PSK, while allowing for low cost transceivers.

- Around one third of measured cases correctly demodulated 8PSK so it was decided to include non-binary constellations in the specification.

All technical decisions made and included in the PHY specification are the result of the analysis of several options that were preliminarily implemented and tested on field. Hence the final decisions achieve a good compromise in terms of performance, flexibility and cost for the majority of measurements.

B. PRIME MAC

The MAC layer was defined for a connection-oriented master/slave configuration, and is optimized for the LV power line environment. Well known procedures and mechanisms from other public standards have been included.

A specific addressing scheme is defined to identify subnetworks and different types of nodes, manage connections and perform multicast and broadcast. Connections are needed for communication of nodes in the system.

PRIME devices will mostly be used in applications which generate small or very small bursts of traffic, which may have real time delay requirements. For this reason, channel access scheme is mainly based on CSMA/CA (Carrier sense multiple access with collision avoidance), although it is possible to reserve Contention Free Periods for certain types of traffic. Time is divided into fixed size frames and transmission of a beacon by Base Node identifies the start of a frame.

In the PRIME architecture, one subnetwork is defined in the context of a single transformer and its meters. A subnetwork with 'n' elements is a tree with two types of nodes, the (1) Base Node and the (n-1) Services Nodes.

- The Base Node is at the root of the tree and acts as the master node that provides connectivity to the subnetwork. It also manages the subnetwork resources and connections. The Base Node is initially the subnetwork itself, and the other nodes should follow a process of registering in order to enroll themselves on this subnetwork.
- Any other node of the subnetwork is a Service Node. Service Nodes are either leaves or branches of the tree. These nodes configure themselves to establish network connectivity up to the Base Node. A Service Node can operate in a Terminal state or in a Switch state. In the latter case it provides for connectivity inside the subnetwork, by means of the implemented repeating mechanisms.

Repeating function is defined as an integral part of the MAC layer for purposes of scalability and range extension. Switch Nodes are the ones that perform the repeating function, which includes

- Transmitting beacons at regular intervals so that new Terminal Nodes can synchronize to the network and existing Terminal and Switch Nodes keep synchronized.
- Relaying data and control packets to/from nodes in their domain from/to the Base Node.

Additionally, a Selective Repeat ARQ (Automatic Repeat-Request) mechanism is used for error control so that MAC layer could ask for PHY retransmission whenever it is needed.

With regard to Security, PRIME is currently using flexible key management policies and 128-bit AES (Advanced Encryption Standard) to provide privacy, authentication and data integrity.

PRIME MAC layer can provide services to a traditional IEC61334-4-32 LLC layer or directly to IPv4. A convergence sublayer to IPv6 has also been developed. PRIME is designed to use DLMS/COSEM as its application layer. Currently v1.3 of the PHY and MAC specification is published and available for download from [17].

C. PRIME Status

Since 2007, continuous field testing is being performed in several hundreds of sites from various European cities, in order to further tune details of the specifications. A deployment of more than 25000 PRIME-compliant meters in Spain is currently being analyzed, with performances well above traditional single carrier systems both in meter reading rate and availability. The application level data rate is about 50% of the PHY raw speeds. This data rate is much higher than what is achievable by earlier PLC systems and will allow fast meter reading and real time interaction from utility control centers to large numbers of remote devices.

PRIME-compliant chipsets are currently produced by Fujitsu Microelectronics, ADD Semiconductor, STMicroelectronics, Texas Instruments and ZIV Group (Figure 4). Some meter manufacturers which provide PRIME systems are Circutor, Itron, Landis+Gyr, Orbis, and Sagemcom.

Work is being undertaken to propose PRIME as an open European standard under the OPEN meter project [19].



Figure 4: PRIME Base Node implementation

VI. CONCLUSION

Power line communications for distribution automation have progressed from low rate one-way systems to high rate bi-directional systems over many years. Modern PLC systems will be one of the enabling technologies for the Smart Grid. It is instructive, however, to recognize that in many European countries first generation ripple control systems have been in place for more than half a century, and perform load control –

an important part of today's Smart Grid concept – routinely on a daily basis. Second generation PLC systems support bi-directional communication and were mostly deployed for AMR. Each generation has increased data rate typically by two orders of magnitude. Modern third generation high rate systems will support central load control, AMR, and further DA and Smart Grid applications.

ACKNOWLEDGMENT

The ABB author thanks Hansjörg Pffnner of the Regionalwerke Baden for providing us with information about ripple control systems.

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