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APPLICATION NOTE 5676

An Overview, History, and Formation of IEEE P1901.2 for Narrowband OFDM PLC

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Abstract: This application note presents a brief history of how the IEEE® Communications Society sponsored the IEEE P1901.2 working group, which developed a complete, robust low-frequency, narrowband powerline communication (LF NB PLC) standard. It discusses the high-level structure of the LF NB OFDM PLC specification and concludes with some current and specific real-life test data.

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Introduction

This application note presents a brief history of how the IEEE® Communications Society (ComSoc), sponsored the IEEE P1901.2[1] Working Group, which developed a complete, robust low-frequency, narrowband powerline communication (LF NB PLC) standard. The standard is structured around PHY and MAC layers, and several coexistence mechanisms are incorporated to ensure that existing and future standards can be deployed in a straightforward manner. This application note summarizes the structure of an LF NB OFDM PLC specification, along with some specific real-life test data. Readers of this application note should derive a good understanding of how the P1901.2 standard is structured.

The History: the Formative Stages of a Standard

The formation of the P1901.2 Working Group started in early 2009 with PLC discussions among several companies attending automotive standards meetings. The discussions centered on how to standardize on a sub-500kHz PLC solution that would meet the upcoming automotive specifications SAE J2931/3 and ISO/IEC 15118-3. At that time, there was limited standardization effort for PLC solutions above the CENELEC® (European Committee for Electrotechnical Standardization) band in the low-frequency (FCC and lower) range. Further discussions took place mid-November 2009 in Denver, Colorado at a NIST-sponsored PAP15 meeting, where NIST (National Institute of Standards and Technology) outlined the need for powerline standards with global coexistence. After additional meetings and with direction from the Board of Governors of the IEEE ComSoc, it was determined that the best path forward would be to approach IEEE for sponsorship of a new standard effort for a PLC solution below 500kHz.

A table similar to **Figure 1** was presented to the IEEE ComSoc in late 2009. At this meeting, the IEEE ComSoc agreed to sponsor a new standard development around LF NB PLC.

Standards for Low- and High-Data-Rate PLC Solutions—Missing LF NB

	FREQ BAND	DATA RATE
IEC 61334	CENELEC	2.4kbps, effective
ISO/IEC 14908-1	CENELEC	5.0kbps, effective
HomePlug® CC	CENELEC	7.5kbps, effective
LF NB Maxim Integrated MAX2990	CENELEC-FCC	100kbps, effective
LF NB G3-PLC	CENELEC-FCC	200kbps+, effective
LF NB PRIME	CENELEC	125kbps, theoretical
HomePlug 1.0	> 2MHz	14Mbps, theoretical
IEEE P1901* Dual PHY/MAC	> 2MHz	200Mbps+, theoretical
ITU G.hn*	> 2MHz	200Mbps+, theoretical

*Standards in development at time of presentation.
Figure 1. Summary table of PLC standards in existence or in development in 2009, with purple boxes highlighting present PLC solutions where no standards exist.

Consequently, the next step was to generate a working group PAR (project authorization request). Over the next month, a PAR[2] was developed, submitted, and approved with the following scope:

> This standard specifies communications for low frequency (less than 500 kHz) narrowband power line devices via alternating current and direct current electric power lines. This standard supports indoor and outdoor communications over low voltage line (line between transformer and meter, less than 1000 V), through a transformer low-voltage to medium-voltage (1000 V up to 72 kV) and through transformer medium-voltage to low-voltage power lines in both urban and in long distance (multi-kilometer) rural communications. The standard uses transmission frequencies less than 500 kHz. Data rates will be scalable to 500 kbps depending on the application requirements. This standard addresses grid to utility meter, electric vehicle to charging station, and within home area networking communications scenarios. Lighting and solar panel power line communications are also potential uses of this communications standard. This standard focuses on the balanced and efficient use of the power line communications channel by all classes of low frequency narrow band (LF NB) devices, defining detailed mechanisms for coexistence between different LF NB standards developing organizations (SDO) technologies, assuring that desired bandwidth may be delivered. This standard assures [sic] coexistence with broadband power line (BPL) devices by minimizing out-of-band emissions in frequencies greater than 500 kHz. The standard addresses the necessary security requirements that assure [sic] communication privacy and allow use for security sensitive services. This standard defines the physical layer and the medium access sub-layer of the data link layer, as defined by the International Organization for Standardization (ISO) Open Systems Interconnection (OSI) Basic Reference Model.[3]

With additional explanatory notes:

> The effort will consider existing narrowband powerline communications technologies, which operate below 500 kHz, as a starting point, and will review coexistence, EMC, and performance data in the application scenarios covered. The standards initiative will harmonize with technologies operating in the same field (LF NB), data rate (scalable to 500 kbps) and frequency band (frequencies 500 kHz and lower), along with unifying ongoing global smart grid PLC projects). IP addressing will also be a priority with consideration for IPv6 or IPv6/IPv4 dual stack to support legacy device operation. These will form the basis for detailed scope of task group that will work within P1901.2 to develop the components of the final standard.[4]

As a result of the approved PAR, the IEEE P1901.2 Working Group formed several subgroups to address solutions for various key areas. These areas included harmonization technologies operating in a low-frequency band; robustness for through-transformer communication; defining limits and testing for EMC; defining a complete coexistence mechanism with existing SDO technologies; and prioritizing IP addressing.

Figure 1 shows that in 2009 there were only a few low-frequency orthogonal frequency-division multiplexing (OFDM) PLC technologies in production to accompany the widely deployed CENELEC-band FSK technologies already approved as international standards. The low-frequency OFDM PLC solutions included PRIME, which supports CENELEC bands,[5] and G3-PLC, which supports CENELEC through the FCC bands.[6] Consequentially, to harmonize with technologies operating in the same field (i.e., LF NB), a decision was made to use PRIME and G3-PLC as the basis for IEEE P1901.2.[7]

A coexistence subgroup was formed to address the challenges of managing a fair mechanism that was not overly complex and would be globally applicable. An EMC subgroup was formed to define extended global EMC limits beyond existing limits (existing limits were not complete for above the CENELEC and ARIB—Association of Radio Industries and Businesses—bands). The EMC subgroup was additionally tasked to develop test criteria to meet these limits.

OFDM PLC Structure Overview

An OFDM PLC standard requires that the specifications for several layers of the OSI model be defined. This includes Layer 1 Physical (PHY) with frame structure and primitives, and Layer 2 Media Access (MAC) to regulate access to the medium by using carrier sense multiple access with collision avoidance (CSMA/CA). The MAC also includes a tone map response command and accompanying neighbor table. The PHY and MAC layer specifications are also highly dependent on the application frequency bands.

To address the challenging PLC environment, both PRIME and G3-PLC took similar approaches in their OFDM PLC PHY solution. G3-PLC included some additional features such as robust mode, adaptive tone mapping (ATM), and two-dimensional interleaving to cover scenarios with more severe noise impairments. G3-PLC also addressed LV to MV and MV to LV communication. These features were also adopted in the various new LF NB OFDM standards.

To address global regulations, three main bands were defined: the CENELEC band (Europe, CENELEC bands A, B, C, and D), which has an upper limit of approximately 150kHz; the ARIB band (Japan), which has an upper limit of approximately 450kHz; and the FCC (Federal Communications Commission) band (multiple countries), which has an upper limit of approximately 500kHz. Although these bands have definitive upper limits, it is customary to define subbands within these limits, both to maximize system parameters for optimal performance in varying conditions and to maximize shared bandwidth. An example of this would be an FCC subband, which has a start frequency above the CENELEC bands at 154.6875kHz and a stop frequency at 487.5kHz. Because of the inherently low EMC emissions (and, consequently, limited wireless crosstalk), properly defined LF NB solutions can transmit in frequency bands with a relatively small guardband without disturbance-related issues.

Each subband is defined with a start and stop frequency and with a specific number of subcarriers (tones) per band. Once the number of carriers is defined, a table is generated that indicates the phase vector definition per carrier. With the known number of carriers per symbol, along with the number of symbols per PHY frame and the number of parity bits added by FEC blocks, the PHY data rate can be calculated. The number of symbols in each PHY frame is selected based on two parameters: the required data rate and the acceptable robustness. As an example, for the FCC subband with a start frequency of 154.6875kHz and a stop frequency of 487.5kHz, the determined number of subcarriers is 72.

The PHY Layer

Details on PHY building blocks have been presented in various IEEE publications. The ultimate result is a now universal, PHY structure for NB PLC.[8]

The fundamental PHY elements in the transceiver start with the scrambler. The scrambler's function is to randomize the incoming data. Both G3-PLC and PRIME utilize the same generator polynomial:

$$s(x) = x^7 + x^4 + 1 \quad \text{(Eq. 1)}$$

Two levels of error correction follow, starting with a Reed-Solomon (RS) encoder where typically data from the scrambler is encoded by shortened systematic Reed-Solomon (RS) codes using Galois Field (GF). The second level of error correction, employed by both G3-PLC and PRIME, uses a 1/2 rate convolutional encoder with constraint rate K = 7. The convolutional encoder is followed by a two-dimensional (time and frequency) interleaver. Together these blocks significantly improve robustness and overall system performance in the presence of noise.[9]

Following the FEC is the OFDM modulator. (The modulation technique of PRIME and G3-PLC was the selected modulation to be used in IEEE P1901.2.) The defined modulator describes the modulation (BPSK, QPSK, 8PSK, etc.); the constellation mapping; the number of repetitions (4, 6, etc.); the type of modulation (differential, coherent); the frequency domain pre-emphasis; OFDM generation (IFFT, with cyclic prefix); and windowing.

Frame Structure

Structure of the physical frames is defined according to the fundamental system parameters, including the number of FFT points and overlapped samples, the size of cyclic prefixes, the number of symbols in the preamble, and the sampling frequency. The physical layer supports two types of frames: the data frame and the ACK/NACK frame. Each frame starts with a preamble used for synchronization and detection, as well as automatic gain control (AGC) adaptation. The preamble is followed by data symbols allocated to the frame control header (FCH) with the number of symbols depending on the number of carriers used by the OFDM modulation.

The FCH is a data structure transmitted at the beginning of each data frame. It contains information regarding modulation and the length of the current frame in symbols. The FCH also includes a frame control checksum (CRC, or cyclic redundancy check), which is used for error detection. The size of the CRC depends on the frequency band being utilized.

Adaptive Tone Mapping (ATM)

To complete the suite of PHY layer features needed to optimize maximum robustness, ATM is required. The added ATM feature is implemented first by estimating the SNR of the received signal subcarriers (tones), and then adaptively selecting the usable tones and the optimum modulation and coding type to ensure reliable communication over the powerline channel. Tone mapping also specifies the power level for the remote transmitter and the gain values to be applied for the various sections of the spectrum. The per-carrier quality measurement enables the system to adaptively avoid transmitting data on subcarriers with poor quality. Using a tone map indexing system, the receiver understands which tones are used by the transmitter to send data and which tones are filled with dummy data to be ignored. The goal of the ATM is to achieve the greatest possible throughput under the given channel conditions between the transmitter and the receiver.[10]

PHY Data Primitives

With the physical layer transceiver specifications complete, the transmission protocol between the MAC and the PHY layer must be defined. This protocol includes different data primitives accessible between the MAC and PHY layers.

Three primitives are introduced. The PD-DATA.request primitive is generated by a local MAC sublayer entity and issued to its PHY entity to request the transmission of a PHY service data unit (PSDU). The PD-DATA.confirm primitive confirms the end of the transmission of a PSDU from the local PHY entity to a peer PHY entity. The PD-DATA.indication primitive indicates the transfer of a PSDU from the PHY to the local MAC sublayer entity.

PHY Management Primitives

The PHY layer includes a management entity called the PLME (physical layer management entity). The PLME provides layer-management service interfaces functions. It is also responsible for maintaining the PHY information base (IB).

The PLME-SET.request/confirm and PLME-GET.request/confirm primitives allow access to the PHY IB parameters. The PLME-SET-TRX-STATE.request/confirm primitives control the state of the PHY TX/RX. The PLME-CS.request/confirm primitives get the media status using physical carrier sense.

The MAC Layer

The MAC layer is an interface between the logical link control (LLC) layer and the PHY layer. The MAC layer regulates access to the medium by using CSMA/CA. It provides feedback to upper layers in the form of positive and negative acknowledgements (ACK or NACK) and also performs packet fragmentation and reassembly. Packet encryption/decryption is carried out by the MAC layer as well.[11]

Tone Map Response

The tone map response MAC command is needed to utilize adaptive tone mapping. The MAC sublayer generates a tone map response command if the tone map request (TMR) bit of a received packet segment control field is set. This means that a packet originator has requested tone map information from a destination device. The destination device must estimate this particular communication link between two points and report the optimal PHY parameters. The tone map information includes the index associated with PHY parameters: the number of used tones and allocation (tone map), the modulation mode, the TX power control parameters, and the link quality indicator (LQI).[12]

The Neighbor Table

Every device must maintain a Neighbor Table that contains information for all devices that can be communicated with directly. A Neighbor Table element is created once a frame is received from a neighbor device and updated with optimum PHY transmission parameters as soon as a tone map response command is received. This table must be accessible by the adaptation and MAC sublayers. Each entry of this table would contain the TX parameters (tone map, modulation, TX gain) that can be used to communicate with the neighbor device.[13]

Coexistence

To complete an OFDM PLC specification beyond PHY and MAC specifications, an additional critical detail is defining a robust and reliable coexistence mechanism. There are several coexistence mechanisms already deployed for narrowband technologies. FCC subband enables one form of coexistence (frequency separation). Another coexistence mechanism utilizes a notching technique, also referred to as tone masking. The notching method is used to avoid certain frequencies that are reserved by powerline regulatory bodies for other applications; it also allows for cohabitation with PLC S-FSK systems and cohabitation with other potential systems operating on a powerline. However, to meet the IEEE 1901.2 objective of developing a complete coexistence mechanism, additional mechanisms are required.

Preamble-Based Coexistence Mechanism

After careful study, the IEEE P1901.2 Working Group determined that a third coexistence mechanism was required for new narrowband OFDM PLC standard solutions being introduced to the market. This third mechanism, preamble-based, meets this requirement; it allows different narrowband PLC solutions to coexist with fairness and minimal disruption of service.

A preamble-based coexistence mechanism employs a fixed number of neutral coexistence preamble symbols at a specific frequency, or multiples of a specific frequency, depending on the band plan. The implementation process involves several procedures. The use of a coexistence mechanism is dependent on the technology type and region of deployment. Control PIB attributes are defined to set default values that enable or disable preamble-based CSMA solutions. For example, an IEEE 1901.2 solution, which implements only a CENELEC A-band plan in a region where energy providers control the CENELEC A frequency band, would most likely not be able to implement a preamble-based CSMA coexistence mechanism. Instead, the solution must rely on existing frequency separation or notching techniques.[14]

Field Trial Data

Early testing of NB LF OFDM PLC has shown that IEEE 1901.2 is based on a reliable, robust technology. Much of the initial global testing has involved tens of units to ten thousands or more units. This is illustrated in examples such as the PRIME deployment in Spain, where PRIME continues to be successfully deployed.[15] Field trial information has been presented in various technical conferences with additional information available on the PRIME Alliance website.

The Devolo® corporation performed initial testing of an early G3-PLC™ FCC band in Europe in 2012 and has observed particularly promising results. Devolo's early testing sought to determine a number of parameters, such as round-trip relay time, bandwidth in the physical layer, calculation of bandwidth in the application layer, accessibility of the nodes, channel measurement, analysis of the lead time for parameterizing, and firmware upload to the meters.[16]

Figure 2 illustrates the PLC communication topography in their testing and **Figure 3** shows the application layer data rates achieved.

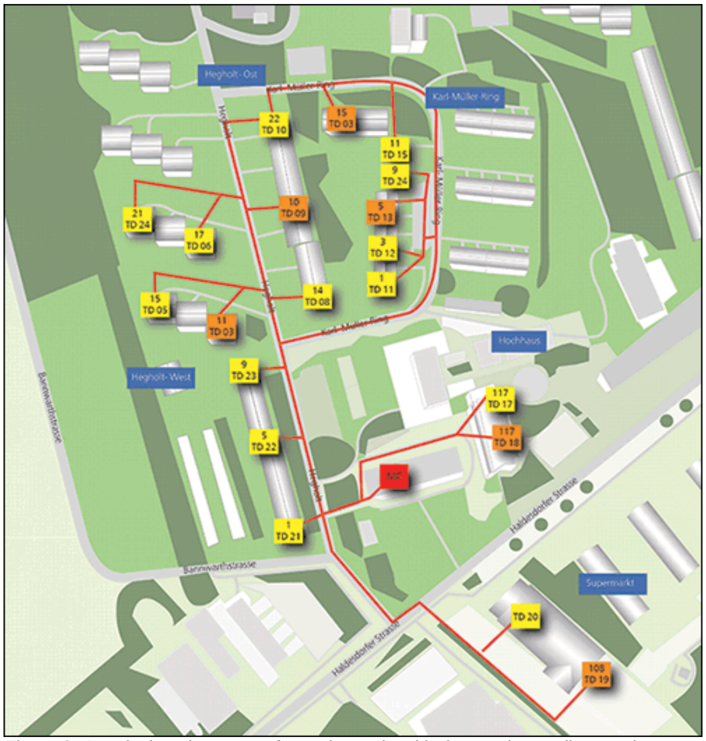

Figure 2. A typical environment of an urban grip with the maximum distance between nodes at 20m. Installation of one access node in a substation and installation of 22 nodes at one customer's premises. Image supplied courtesy of Devolo AG.

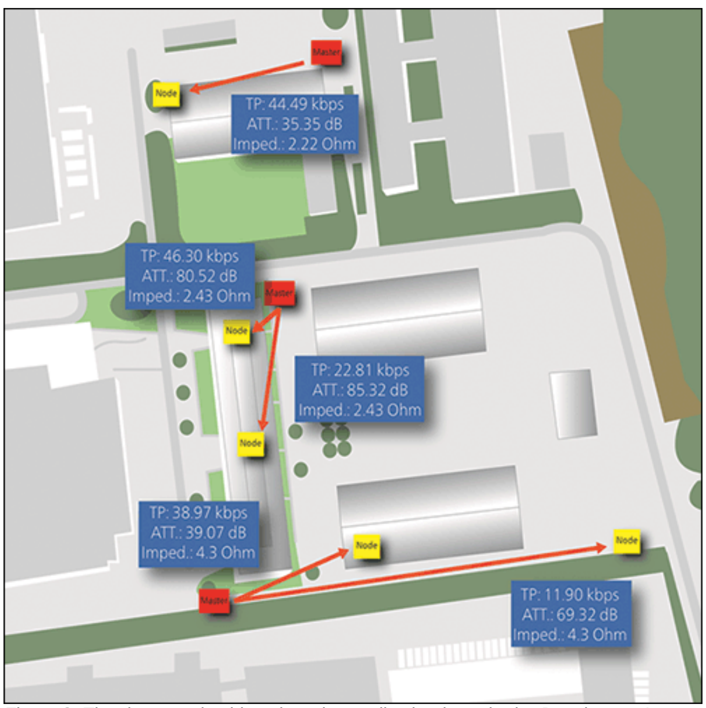

Figure 3. The data rated achieved on the application layer in the Devolo test. Image supplied courtesy of Devolo AG.

In another field trial, Enexis commissioned a study for 1000 LF NB OFDM PLC communication-enabled meters in 2012 in the Netherlands. This test evaluated the reliability, robustness, and connectivity of G3-PLC meters for their utility grid. Initial results showed that with minimal to no additional adjustments, immediate connectivity could be achieved. As a result, after initial installation, 99% of meters were immediately discovered by the data concentrator. Additionally, 98% of the meters met performance parameters for data collection every 15 minutes. (Note that this testing occurred in a lightly populated topography with limited routing options.)

Summary

This application note has outlined a brief history of the development of the IEEE 1901.2 standard. The standard itself is a complete, extensive document, so the summary of the specification in this application note consciously omits many details. Instead, it discusses the high-level structure of the LF NB OFDM PLC specification and concludes with some current and specific real-life test data. Readers should now have a basic understanding of how the P1901.2 standard is structured and the effectiveness of early field trials.

Some of the information in this application note is discussed in the chapter “Narrowband Power Line Standards” in a new book titled *MIMO Power Line Communications: Narrow and Broadband Standards, EMC, and Advanced Processing*. Publication is expected in the fall of 2013.[17]

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Related Parts		
MAX2990	10kHz to 490kHz OFDM-Based Power Line Communications Modem	Free Samples
MAX2991	Power-Line Communications (PLC) Integrated Analog Front-End Transceiver	Free Samples
MAX2992	G3-PLC MAC/PHY Powerline Transceiver	Free Samples

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