

4th-generation HD-PLC Quatro

Core Overview (English)



Owned By **HD-PLC ALLIANCE**

Contributed By Panasonic Corporation

Fourth-generation HD-PLC Quatro Core Overview

Panasonic Corporation

1. Introduction

"HD-PLC," a technology for high-speed power line communication, was standardized in 2010 as IEEE 1901. However, with the widespread of IoT networks, a growing range of software is being used, creating situations where the IEEE 1901 version on HD-PLC needs to be upgraded to offer longer communication distances and faster communication speeds. Many users are now demanding these types of improvements.

Let's discuss communication distance issues first. HD-PLC was originally designed as a communications infrastructure technology to improve domestic lifestyles. It provides networks in which housing equipment, household appliances, sensors, etc., are permanently connected to the Internet. For building energy management systems (BEMS), factory energy management systems (FEMS), smart meters, etc., the distances between different terminals are mostly longer than for domestic use. HD-PLC-based networks must, therefore, be robust enough to allow terminals to communicate with each other in all given indoor communication environments.

To solve the above distance-related challenge, multi-hop technology, such as ITU-T G9905, originally published in 2013 and amended in 2016, has been developed for PLC. (We will discuss multi-hop technologies below, in Chapter 3.) Even if multi-hop technology greatly improved long range communication, the fact that power line distribution systems are usually built into star and tree structures makes sometime difficult to install terminals in optimum locations to achieve better signal quality, and in some cases multi hop technology is not enough to reach an isolated and distant PLC terminal.

We now come to communication speed issues. In the fields of security, entertainment, etc., high-definition video images (4K/8K) are captured by cameras connected to transmission paths composed of coaxial cables, and faster transmission of these images is now required. A network based on IEEE 1901 version HD-PLC offers a maximum physical line transmission rate (theoretical value) of 240 Mbps in the 2 - 28 MHz band. When such networks also include various pieces of application software as described above, the network's transmission speed may become insufficient.

HD-PLC Quatro Core has been designed to solve these problems. Specifications based on this technology were approved as IEEE 1901a in March 2019, and published as IEEE 1901a-2019 standard in May in the same year. IEEE 1901a is an improvement on the conventional IEEE 1901 in both communication distance and speed. It achieves to double IEEE 1901's communication distance by adopting a communication band of 1/2 or 1/4 of IEEE 1901 band, and achieves to offer a maximum physical line transmission rate of 1 Gbps by using an expanded communication band 2 or 4 times the IEEE 1901 band.

This document provides a summary of the HD-PLC Quatro Core technology and an introduction to some of its functions. The multi-hop technology used in third-generation HD-PLC is also included to fourth-generation HD-PLC Quatro Core, and will therefore be described as we discuss the HD-

PLC Quatro Core technology.

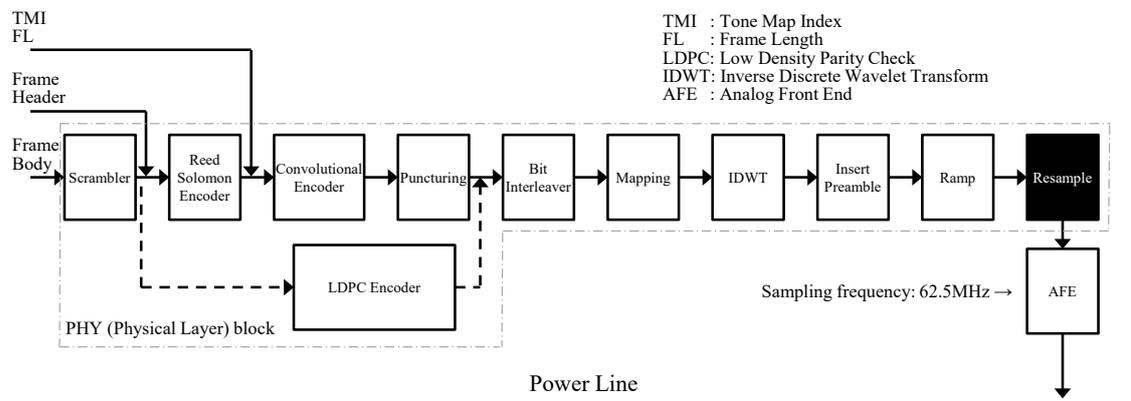


Figure 1.1. Flexible channel wavelet OFDM transmitter

2. HD-PLC Quatro Core technology

This technology is different from IEEE 1901-version HD-PLC in that a Wavelet OFDM transmitter executes an additional resampling process (Fig. 1.1). This gives the HD-PLC Quatro Core the new function of switching between long-distance communication mode and high-speed communication mode while maintaining its compatibility with IEEE 1901 version HD-PLC.

2.1 Long-distance communication and high-speed communication

When power line communication (PLC) technology is used for B-to-B (business-to- business) communications involving BEMS, FEMS, smart meters, etc., and for B-to-C (business-to-consumer) communications involving residential equipment, household appliances, sensors, etc., communication across long distances with high robustness is a key factor. This is because network equipment is installed in very different types of locations, such as commercial buildings and factories for B-to-B communications; and B-to-C communications such as in condominiums are affected by power line noise and interference from domestic electrical devices. In both cases, therefore, improved terminal connectivity and reliable communication are required.

To improve the stability of communication, the signal-to-noise ratio (SNR) in the communication band needs to be raised: in other words, signal attenuation and noise in the communication band must be reduced. However, power lines, which differ from ordinary communication lines, are laid in a rather disadvantageous communication environment: no impedance is specified for power lines, many branch nodes are present, and various kinds of loads (electrical devices) are connected to them. To improve the SNR of power lines to allow them to function as reliable communication paths, therefore, communication through them must be performed using a band that has less attenuation and noise.

Measuring the transmission characteristics of a single-line cable serving as a power line reveals that signal attenuation is greater at higher frequencies. Figure 2 shows the spectrum of a received PLC signal for a single-line vinyl insulated vinyl sheathed flat cable (VVF) under noiseless

conditions. In a single-line cable, the signal attenuates rapidly in the high frequency band with the increase of cable length. This leads to a situation in which a small proportion of the signal in the low frequency band is unaffected, but the rest of the signal attenuates over the entire communication band, thus failing to achieve a sufficient SNR. In this case, communication fails. To achieve long-distance communication, therefore, it is necessary to use the low frequency band to ensure that a sufficient number of subcarriers remain effective in the communication band. Achieving this configuration requires a function that makes the symbol length variable in line with transmission characteristics, thereby allowing a change in subcarrier intervals.

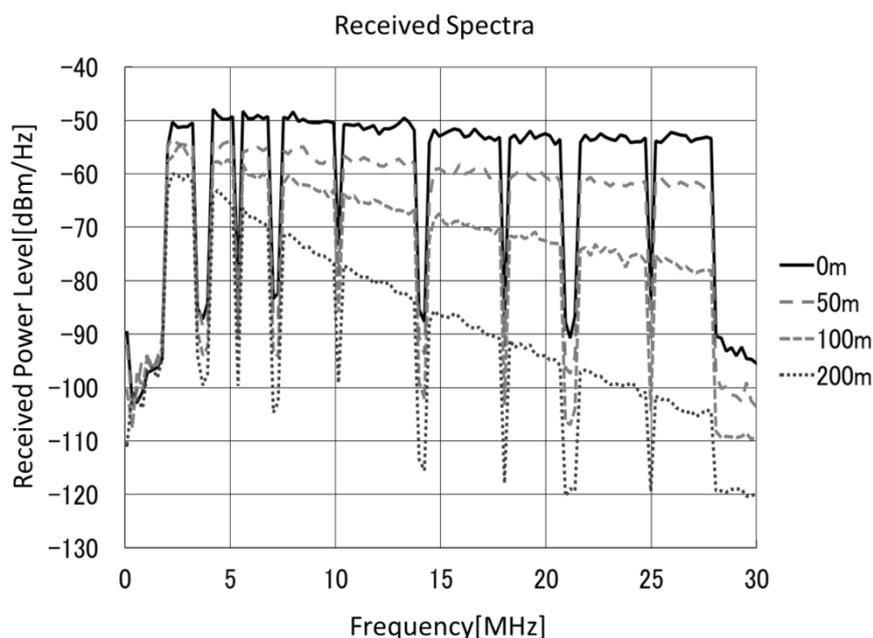


Figure 2.1. Influence of a single-wire VVF cable

In the fields of security, entertainment, etc., today, the video images captured by cameras are in high definition (4K/8K), for which high-speed communication is essential. Dedicated coaxial cables are typically used in such applications. On such cables signal attenuation and noise are lower than on power lines. To achieve high-speed communication in ordinary power lines, we have adopted a system in which the existing Wavelet engine is used to change subcarrier intervals to allow broadband communication.

2.2 Modes and channels

Table 2.1 shows symbol length, frequency offset, and channel ID for each mode. There are nine modes that vary according to the combinations of frequency bands used and the numbers of channels present in the frequency bands. Three kinds of frequency bands are used: the Signal Channel Wavelet (SCW) band (XB1), which is used in IEEE 1901 version HD-PLC; Extended band 2 (XB2), which is two times the SCW band; and Extended band (XB4), which is four times the SCW band. These three frequency bands include one channel, two channels, and four channels, respectively. Figure 2.2 shows the relationship between channel IDs set respectively in the modes and

frequencies. XB1-1Ch mode (Channel ID: x-1) is the mode equivalent to the IEEE 1901 version of HD-PLC, in which communication interoperability with terminals conforming to IEEE 1901 is maintained. In XB1-2Ch mode, the symbol length becomes double than in XB1-1Ch mode, meaning that the subcarrier intervals are now half those of XB1-1Ch mode, in which case two channels (Channel ID: x-2, x-3) can be used by using frequency offset. In this mode, symbol length variations combined with frequency offset allow the formation of 15 channels. The user is, therefore, able to choose the channel that best suits the conditions of the transmission path.

Table 2.1. Frequency offset, symbol length, and channel ID in each mode

Mode	Symbol length [μs]	Frequency offset [MHz]	Channel ID (CID)
XB1-1Ch	8.192	0	x-1
XB1-2Ch	16.384	0	x-2
		15.625	x-3
XB1-4Ch	32.768	0	x-4
		7.8125	x-5
		15.625	x-6
		23.4375	x-7
XB2-1Ch	4.096	0	x-8
XB2-2Ch	8.192	0	x-1
		31.25	x-9
XB2-4Ch	16.384	0	x-2
		15.625	x-3
		31.25	x-10
		46.875	x-11
XB4-1Ch	2.048	0	x-12
XB4-2Ch	4.096	0	x-8
		62.5	x-13
XB4-4Ch	8.192	0	x-1
		31.25	x-9
		62.5	x-14
		93.75	x-15

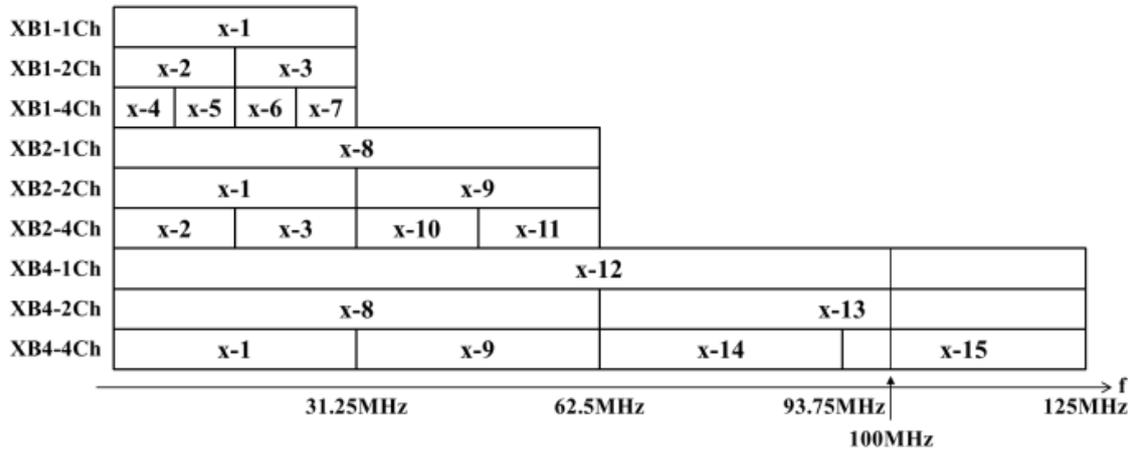


Figure 2.2. Relationship between mode, frequency band, and channel ID

2.3 The resampling process

To change the basic symbol length and subcarrier intervals in the XB1-1Ch mode (IEEE 1901 version HD-PLC), the resampling process is carried out in PLC. Figure 2.3 shows specific examples of the resampling process. Figure 2.3(a) shows the resampling process carried out when the number of channels is two (Channel ID: x-3), and Fig. 2.3(b) shows the resampling process carried out in when the number of channels is four (Channel ID: x-5).

In the case of Fig. 2.3(a), the sampling frequency ($2 \cdot f_{s1}$) is 62.5 MHz. When the sampling cycle is doubled, a signal with a frequency lower than the Nyquist frequency (f_{s1}) comes to have a Nyquist frequency f_{s2} , and is rearranged in a frequency band lower than the Nyquist frequency f_{s2} . The signal is then subjected to sampling at a sampling rate that is double the original sampling rate, which creates aliasing noise in a frequency band higher than the Nyquist frequency f_{s2} , thus changing the Nyquist frequency f_{s2} into Nyquist frequency f_{s3} . The aliasing noise is then eliminated through filtering, which is followed by frequency offset. Hence a channel with ID x-3 is created.

In the case of Fig. 2.3(b), the sampling frequency ($2 \cdot f_{s1}$) is 62.5 MHz, as in the above case. Increasing the sampling cycle fourfold creates a Nyquist frequency of f_{s4} , thus rearranging the signal in a frequency band lower than the Nyquist frequency f_{s4} . The signal is then subjected to sampling at double the original sampling rate, which creates aliasing noise in a frequency band higher than the Nyquist frequency of f_{s4} , thus changing the Nyquist frequency f_{s4} into Nyquist frequency f_{s5} . The aliasing noise is then eliminated through filtering, which is followed by frequency offset to a higher frequency. The signal is then again subjected to sampling at double the original rate, which creates aliasing noise in a frequency band higher than the Nyquist frequency of f_{s5} , thus changing the Nyquist frequency f_{s5} into Nyquist frequency f_{s6} . Finally, the aliasing noise is eliminated through filtering, which creates the channel with ID x-5.

Other channels with different channel IDs are created using the same method, by which signal rearrangement is carried out based on the signal in the XB1-1Ch mode. In actual communication, the transmission characteristics of each channel are estimated to select the most suitable channel to be used. This is done by calculating the respective physical line transmission rates of channels from the

SNRs of subcarriers making up the channels, and then choosing the channel that is the least affected by attenuation and noise.

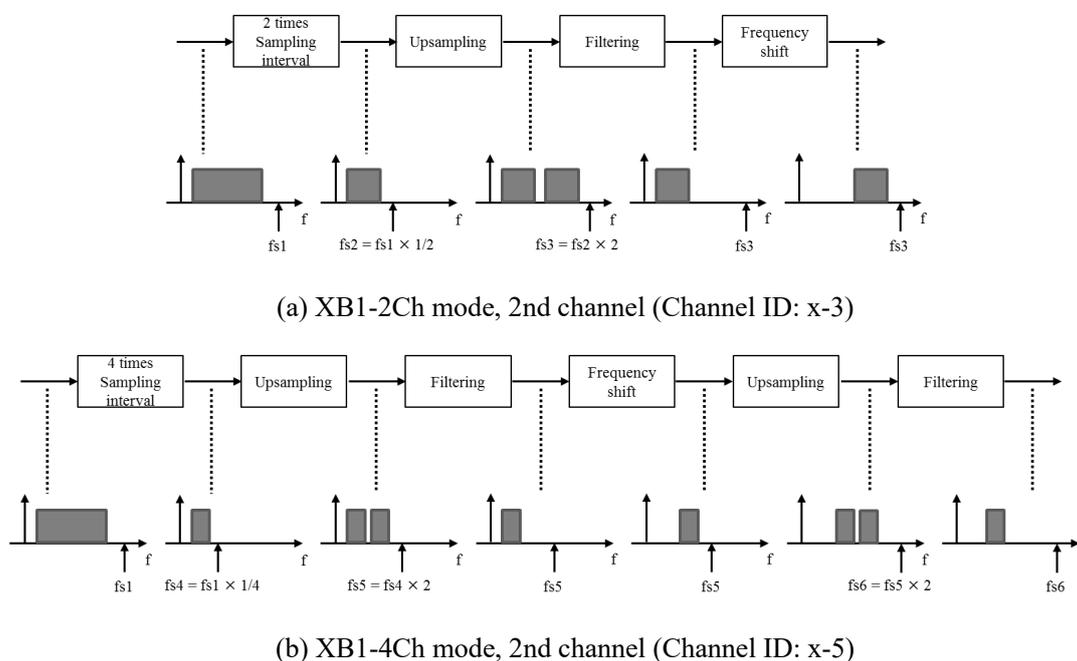


Figure 2.3. Example of resampling process

2.4 Evaluation

This section describes the results of two communication evaluation tests using a field-programmable gate array (FPGA).

2.4.1 Communication characteristics obtained using a simulated VVF cable

In this test, the characteristics of a single-line VVF cable, a type frequently used for indoor wiring, were simulated by inputting data on the attenuation characteristics of VVF cables with different lengths to a commercially-available simulator (PLCS 3000) to model a set of transmission paths.

Figure 2.4 is a graph in which the throughput of channels with IDs (x-1), (x-2), and (x-4) is plotted against the length of the VVF cable. When it is short, the channel with ID (x-1), which uses a wide frequency band, allows high-speed transmission. However, with the increase of the cable length, the channel with ID (x-2) becomes the high-speed path and, finally, the channel with ID (x-4) takes over as the high-speed path. Comparing the respective communication distances of these cables at a transmission rate of 5 Mbps reveals that the communication distance of the channel with ID (x-2) is about 1.7 times that of the channel with ID (x-1), and the communication distance of the channel with ID (x-4) is about 2.5 times that of the channel with ID (x-1). This is because, as indicated in Fig. 2.1, as the single-line VVF cable increases in length, the VVF cable characterized by its drastic signal attenuation in the high-frequency band, demonstrates its reliability in communication modes in which the low frequency band is utilized.

In a communication environment in which actual power lines are used, the characteristics of

transmission paths are more complicated. It is, however, a confirmed fact that the characteristics of cables tend to approach the characteristics shown in Fig. 2.1 when the cable length increases. Communication utilizing a narrow-band channel in the low-frequency band is, therefore, a very useful approach. If colored noise is present in a band with multiple channels, correct estimation of the transmission path allows optimum communication.

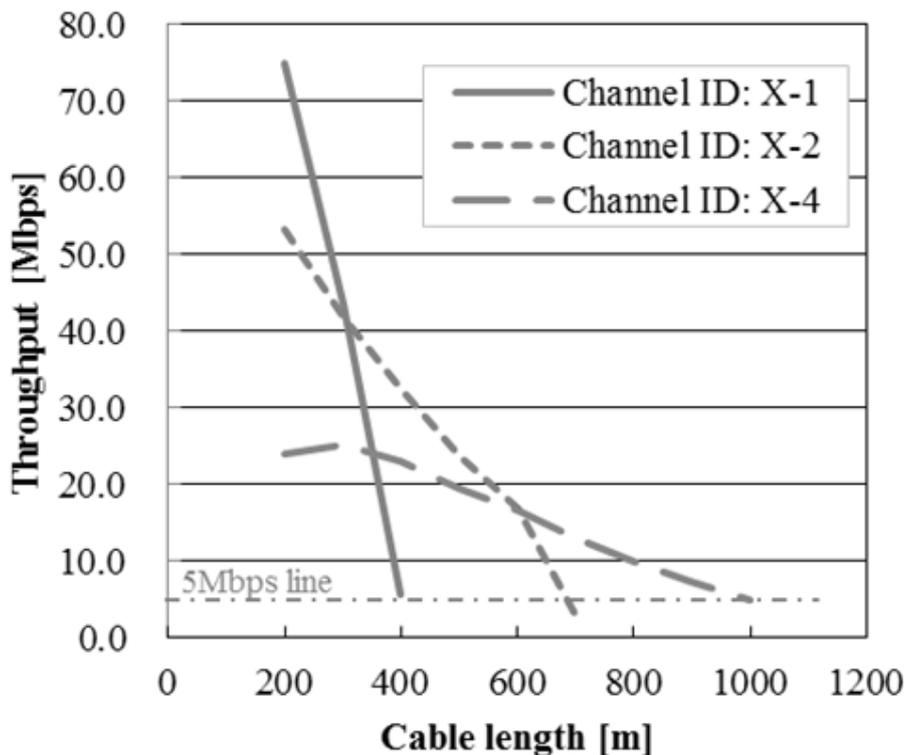


Figure 2.4. Throughput of channel ID (x-1, 2, 4) with FPGA and simulated transmission line

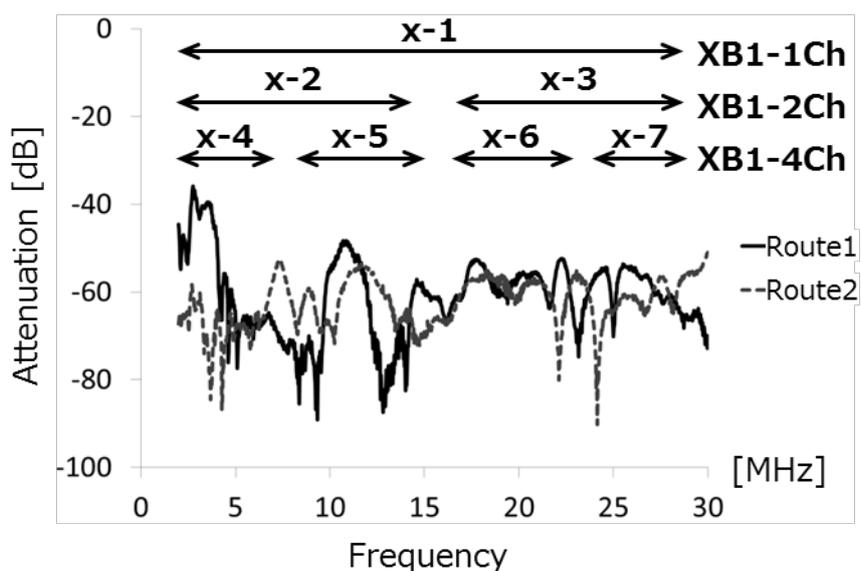


Figure 2.5. Transmission characteristics (Path 1 and Path 2)

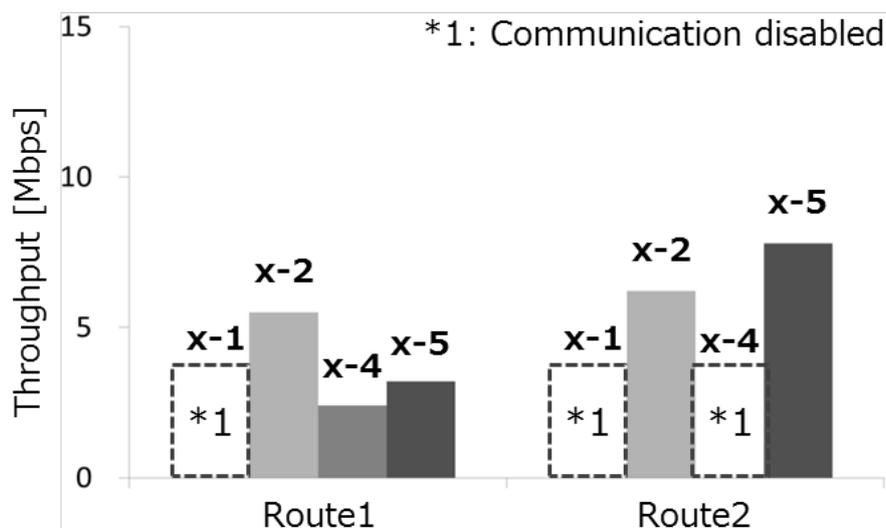


Figure 2.6. Transmission rate with TCP

2.4.2 Communication characteristics obtained in an actual communication environment

In an actual communication environment, one wall outlet and two wall outlets, which are distant from an indoor distribution board, were selected from the first floor and the second floor of a building, respectively, to create two paths, each linking a pair of wall outlets located across both floors (Path 1 and Path 2). The transmission characteristics of each path are shown in Figure 2.5. Each path shows signal attenuation of about 60 dB. Wall outlets in a house are connected to various pieces of electrical equipment, and, when noise from such electric equipment is taken into consideration, it is safe to say that these transmission paths provide an unfavorable communication environment. Figure 2.6 shows the transmission rates of two paths that result when TCP communication is performed between FPGAs. Both paths fail to establish a communication link when the channel with ID (x-1) (IEEE 1901 version HD-PLC) is used. Path 1 allows communication at the highest transmission speed when the channel with ID (x-2) is selected, while Path 2 allows the same when the channel with ID (x-5) is selected. In Japan, transmission power must be reduced by 10 dB to 15 dB in transmissions performed in a frequency band above 15 MHz (channels with IDs (x-3), (x-6), and (x-7)). In this frequency band, therefore, no SNR for effective communication can be secured and, consequently, no link is established. This evaluation test demonstrates the effectiveness of changing the subcarrier intervals and using a band that has less attenuation and noise.

An evaluation test of high-speed communication was carried out in a laboratory in which a static environment with less attenuation was maintained. In this test, an HD-PLC evaluation device (DisLINE) was used as the transmission path, and selecting the channel with ID (x-8) yielded a maximum physical line transmission rate of 450 Mbps in transmission between FPGAs. We consider this result to be appropriate when taking into consideration the fact that the theoretical maximum physical line transmission rate when using the channel with ID (x-8) is 500 Mbps and that the

maximum transmission rate (measured value) of a coaxial LAN converter on the market is about 90% of its theoretical value. A coaxial cable serves as a transmission path on which high-speed communication technology is used, in which case the coaxial cable suppresses noise sufficiently to make it a reliable transmission path. We assume, therefore, that a transmission path in an actual communication environment will demonstrate the same communication characteristics as shown in this test.

The above test results thus indicate that HD-PLC Quatro Core technology is more efficient than conventional technology for improving the robustness and transmission speed of a transmission path.

3. Multi-hop technology for HD-PLC Quatro Core

Multi-hop technology is important for IoT applications in IEEE 1901 networks. Multi-hopping is provided using IUT-T G.9905, a multi-hop routing protocol (centralized metric based source routing: CMSR), which is robust, includes less overhead, and is therefore suitable for large-scale IEEE 1901 networks. The major functions of G.9905 are as follows.

- Highly reliable and rapid route detection

A two-way route between the master and a terminal is detected through the exchange of hello messages with two-way link quality taken into consideration. High-speed mode in which hello messages are exchanged at short intervals during the route detection phase allows rapid route detection.

- Control packets with less overhead

Control packets are limited in function to route detection and maintenance. This allows the generation of control packets, which increase as terminals increase, in $O(N)$ order (N denotes the number of terminals present in the network).

- Sound network

Multiple reliable routes are established in the network. Even if noise develops at a specific point in the network and causes route-breaking, an alternative route is created to keep the network running. In addition, hello messages carrying useful information on the network deliver such information to every terminal.

- Supports flexible packet transmission

Data packets are delivered to both downstream and upstream through source routing and/or hop-by-hop routing. The network also supports terminal-to-terminal communication.

This newly developed multi-hop technology enables 10 hops between terminals at maximum, thus allowing a single master to control up to 1024 terminals. By using HD-PLC multi-hop technology, an extensive network infrastructure can be built between different floors of a building whose design prevents radio communication, using existing power lines such as vertical trunk lines.

Figure 3.1 is a diagram showing an electric wiring system in a three-story building. A PLC adaptor with a master function is installed on a main distribution board (D2) close to a router (internet port), while PLC adaptors, each having a terminal function, are installed on sub-distribution boards and wall outlets, respectively. In this system, most of the wall outlets are connected to an L2-

N phase line. All PLC adaptors, except for adaptors plugged into wall outlets (4), are therefore connected to the L2-N phase line.

Figure 3.2 shows a multi-hop topology resulting from the above setup. Figure 3.2 demonstrates that the whole system connection is established across three hops from the main distribution board (D2). Measurements of the physical line transmission rates (PHY rates) of wall outlets (3) and (4) on a sub-distribution board (D5) indicate that the communication speed drops in the event of inter-phase connection. Effective transmission rates in data transmission from the router to respective wall outlets in each floor range from 10 Mbps to 20 Mbps.

In an ordinary system construction procedure, the network topology of Fig. 3.2 and PHY transmission rates are obtained first. Then, the topology is optimized by checking the PHY transmission rates between PLC adaptors and adjusting the locations of installation of the PLC adaptors on the distribution boards such that no situation can arise in which the communication speed on the upstream side close to the router will drop significantly.

In this example, the main aim is to set up WiFi access points across the whole building. To make this possible, the stairwell area, in which radio signals remain strong, is covered by a radio LAN, while in meeting rooms, in which radio signals tend to be weak, WiFi hotspots are created by connecting radio LAN access points to PLC adaptors using Ethernet cabling.

As demonstrated in this example, PLC is a very useful technology for supplementing a radio communication network.

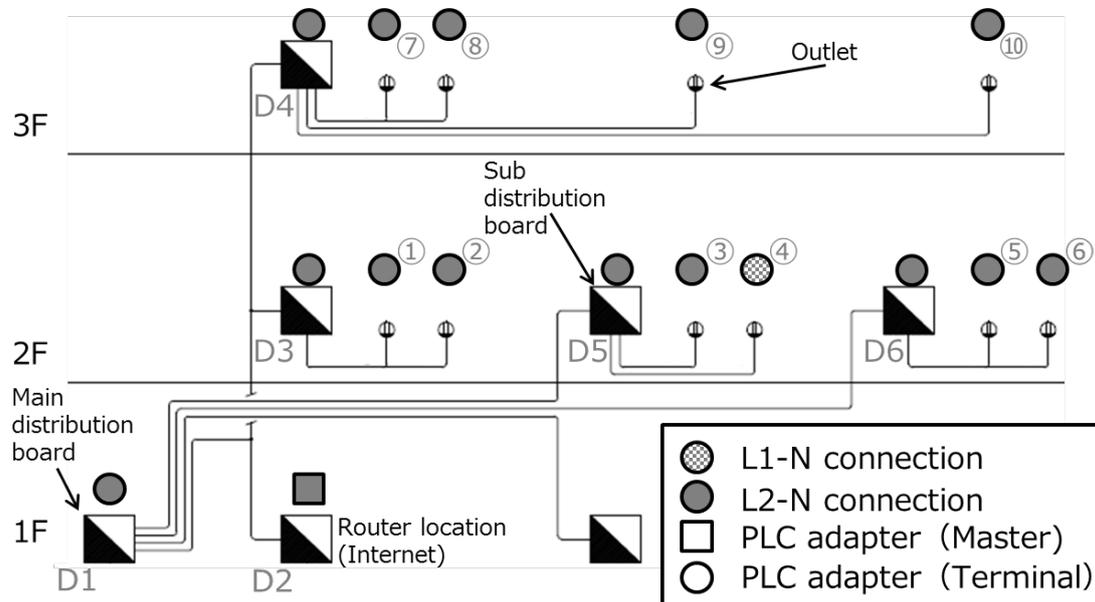


Figure 3.1. Electric wiring system diagram and example of installation

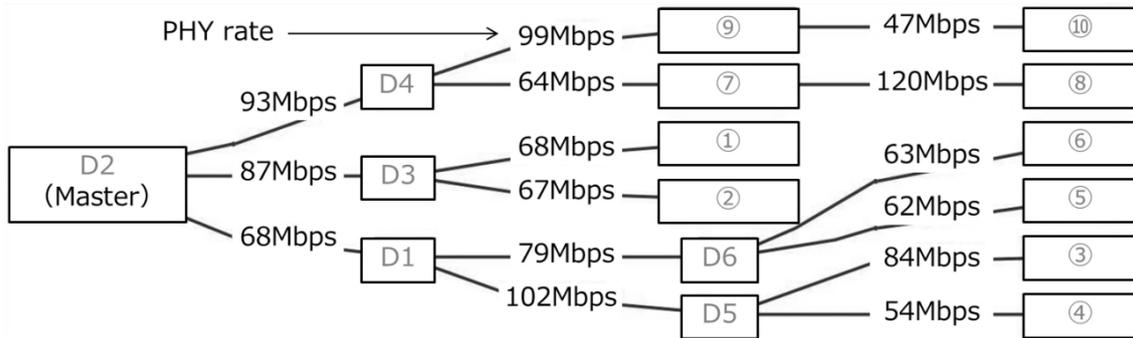
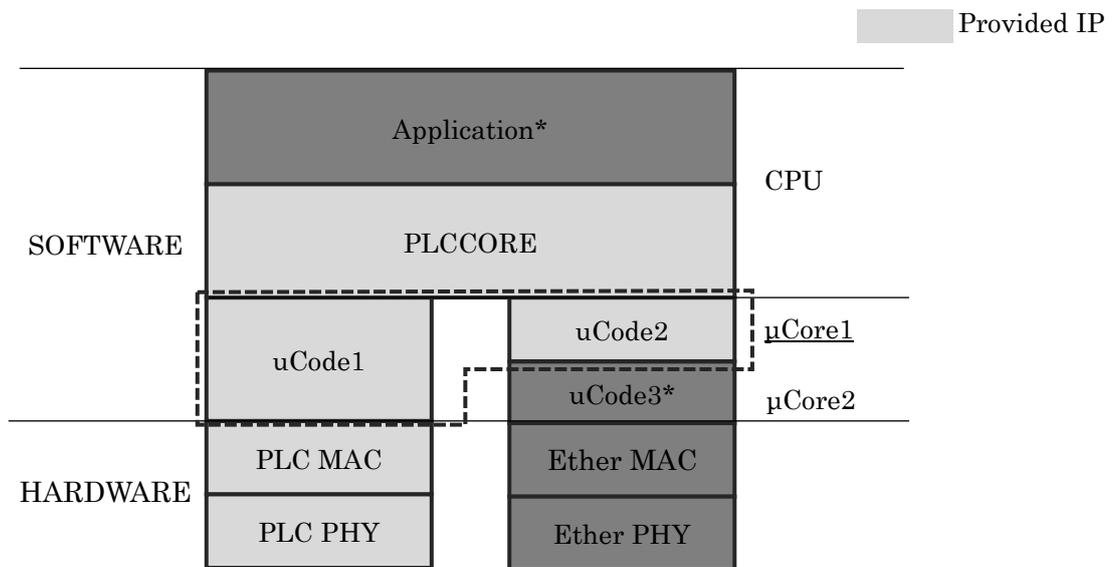


Figure 3.2. The multi-hop topology in Figure 3

4. The software configuration of HD-PLC Quatro Core

The communication functions of HD-PLC are achieved by hardware logics incorporated in an LSI, unique cores (μ Core) included in the hardware logics, and processing by a CPU (Fig. 4.1). Sections 4.1 to 4.5 describe the CPU (PLCCORE), μ Core 1, μ Core 2, PLC MAC, and outline the various functions that PLC PHY offers.



* Samples of Applications and μ Code3 will be provided.

Block name	Form	Outline
Application	Sample source	Application software the user is allowed to modify in any way
PLCCORE	Source	Part of the PLC communication function that is processed by the CPU

uCode1	Object	Unit that processes PLC transmission/reception executed at μ Core1
uCode2	Object	Unit that processes Ethernet transmission/reception executed at μ Core1
uCode3	Sample source	Unit that processes transmission/reception to/from EtherMAC executed at μ Core2 Sample source must be changed in accordance with the EtherMAC adopted.

Figure 4.1 Soft configuration overview

4.1 Outline of functions achieved by CPU (PLCCORE)

Table 4.1 Functions achieved by CPU (PLCCORE)

Functions	Description
Protocol processing	Authentication, ISP (different methods coexisting), simple connection function, transmission path estimation, speed measurement control, etc.
Service interface	External command, internal API, etc.
Terminal control	Control terminals joined to the network.
Classifying control	Control input packet rules defined as rules applied to PLC transfer
Address solution	Provide and control a link between external 802.3 equipment and a PLC terminal.
PLC transmission control	Information control, priority control, multicast conversion, etc., related to PLC transfer.
Response to μ Core	Respond to a control request from μ Core.
Snooping function	Transmission/reception control, robust process, etc., related to multicast transfer that are carried out by snooping on an upper-layer packet
Others	Automatic connection, prohibition of inter-terminal communication, activity monitoring, etc.
Upper-layer processing	Processing related to driver, IP, middle stack, and application software
Multi-hop	Route search, route determining, relay, etc.
CENELEC	Dynamic notch, dynamic power control

4.2 Outline of functions achieved by μ Core1

Table 4.2 Functions achieved by μ Core1

Functions	Description
PLC→ETH transfer	Order control (correction of data overlapping, transmission order, etc.)
PLC→ETH transfer	Address solution, packet classification, multicast transmission
PLC transmission	Framing, ARO, DVTP, CSMA/CA back-off
PLC reception	PHY monitoring, NAV setting, ACK request
Firmware request	Request for creating various control structures, etc.

4.3 Outline of functions achieved by μ Core2

Table 4.3 Functions achieved by μ Core2

Functions	Description
EtherMAC →PLCIP	Copies an Ether packet input to EtherMAC, onto a buffer of PLCIP.
EtherMAC ←PLCIP	Copies a packet from PLCIP onto EtherMAC.
De-aggregation	Divides Ether packets put together by PLCIP into their original forms.
Release of a transmitted packet by primitives	Releases a packet delivered from PLCIP to EtherMAC by communication primitives.

4.4 Outline of functions achieved by PLC MAC

Table 4.4. Functions achieved by PLC MAC

Functions	Description
Frame assembling	Packet assembly/disassembly, CRC addition/check
PLC PHY interface	Tone mapping and data transfer to PLC PHY, receiving data from PLC PHY
Encoding/decoding	Encoding/decoding by AES-128
Media state monitoring	Media state monitoring
Time control	Basic time control on the system
μ Core process support	Back-off process, packet assembly, frame length, NAV calculation logic
Ether transmission/reception control	Ether transmission/reception control, classification
CENELEC	FFT
Coexisting different methods (ISP)	Resource control, timing control

4.5 Outline of functions achieved by PLC PHY

Table 4.5 Functions achieved by PLC PHY

Functions	Description
MAC interface	Function that provides an interface with PLC MAC
Transmission path characteristics estimation	Channel estimation function
Wavelet conversion by OFDM	Modulation and demodulation
Error correction	Reed-Solomon code + convolution code (Viterbi encoding algorithm), LDPC-CC
AFE interface	AFE interface
Coexisting different methods (ISP)	Signal transmission/reception, phase determination
Long-distance communication, high-speed communication	Resampling, frequency shift, channel division

5. Conclusion

HD-PLC Quatro Core, a technology designed for building a network infrastructure for IoT applications that covers both residential spaces and the social infrastructure, has been certified as IEEE 1901a.

HD-PLC Quatro Core has lower communication speed and stability than wired communication using dedicated lines, but is far superior in reliability. It is therefore a communication technology suitable for building an IoT infrastructure in residential spaces, buildings, etc. We anticipate the rapid uptake of this technology.

PLC technology can be used on any kind of electric cable, including power lines. In schools, hospitals, nursing care facilities, etc., for example, coaxial cables for antennas might be routed to individual rooms, while phone lines are laid in other types of non-residential buildings. In such cases, if PLC technology is used, not only power lines but also other existing lines can be used to facilitate network building in existing buildings.

PLC technology also allows mobile IoT equipment to be incorporated into networks, thus allowing PLC technology and the wireless communication technology to be combined to supplement each other. As a result, simpler and more convenient networks can be built.

We hope that the technology described herein will be of great assistance in connecting IoT equipment, which is expected to increase exponentially, to networks.