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Transmission of IPv6 Packets over PLC Networks
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Abstract

Power Line Communication (PLC), namely using the electric-power lines for indoor and outdoor communications, has been widely applied to support Advanced Metering Infrastructure (AMI), especially smart meters for electricity. The inherent advantage of existing electricity infrastructure facilitates the expansion of PLC deployments, and moreover, a wide variety of accessible devices raises the potential demand of IPv6 for future applications. This document describes how IPv6 packets are transported over constrained PLC networks, such as ITU-T G.9903, IEEE 1901.1, IEEE 1901.2 and IEEE 1901.2a.

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1. Introduction

The idea of using power lines for both electricity supply and communication can be traced back to the beginning of the last century. With the advantage of existing power grid, Power Line Communication (PLC) is a good candidate for supporting various service scenarios such as in houses and offices, in trains and vehicles, in smart grid and advanced metering infrastructure (AMI). Such applications cover the smart meters for electricity, gas and water that share common features such as fixed position, large quantity, low data rate, and long life time.

Although PLC technology has evolved over several decades, it has not been fully adapted for IPv6 based constrained networks. The 6Lo related scenarios lie in the low voltage PLC networks with most applications in the area of Advanced Metering Infrastructure (AMI), Vehicle-to-Grid communications, in-home energy management and smart street lighting. IPv6 is important for PLC networks, due to its large address space and efficient address auto-configuration. A comparison among various existing PLC standards is provided to facilitate the selection of the most applicable standard in particular scenarios.

The following sections provide a brief overview of PLC, then describe transmission of IPv6 packets over PLC networks. The general approach is to adapt elements of the 6LoWPAN specifications [[RFC4944](#)], [[RFC6282](#)], and [[RFC6775](#)] to constrained PLC networks. Compared to [[I-D.popa-6lo-6loplc-ipv6-over-ieee19012-networks](#)], this document provides a structured and greatly expanded specification of an adaptation layer for IPv6 over PLC (6LoPLC) networks.

2. Requirements Notation and Terminology

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in

[\[RFC2119\]](#).

This document often uses the following acronyms:

6LoWPAN: IPv6 over Low-Power Wireless Personal Area Network

AMI: Advanced Metering Infrastructure

BBPLC: Broadband Power Line Communication

CID: Context ID

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DAD: Duplicate Address Detection

EV: Electric Vehicle

HDPLC: High Definition Power Line Communication

IID: IPv6 Interface Identifier

IPHC: IP Header Compression

LAN: Local Area Network

LOADng: Lightweight On-demand Ad-hoc Distance-vector Routing
Protocol Next Generation

MSDU: MAC Service Data Unit

MTU: Maximum Transmission Unit

NBPLC: Narrowband Power Line Communication

OFDM: Orthogonal Frequency Division Multiplexing

PCO: PAN Coordinator

PLC: Power Line Communication

PSDU: PHY Service Data Unit

RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks

RA: Router Advertisement

WAN: Wide Area Network

[3.](#) Overview of PLC

PLC technology enables convenient two-way communications for home users and utility companies to monitor and control electric plugged devices such as electricity meters and street lights. Due to the large range of communication frequencies, PLC is generally classified into two categories: Narrowband PLC (NBPLC) for automation of sensors, and Broadband PLC (BBPLC) for home and industry networking applications. Various standards have been addressed on the MAC and PHY layers for this communication technology, e.g. BBPLC (1.8–250 MHz) including IEEE 1901 and ITU-T G.hn, and NBPLC (3–500 kHz) including IEEE 1901.2 [[IEEE 1901.2](#)], ITU-T G.9902 (G.hnem), ITU-T G.9903 (G3-PLC) [[ITU-T G.9903](#)] and ITU-T G.9904 (PRIME). And

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moreover, recently a new PLC standard IEEE 1901.1 [[IEEE 1901.1](#)], which aims at the medium frequency band less than 12 MHz, has been published by the IEEE standard for Smart Grid Powerline Communication Working Group (SGPLC WG).

Narrowband PLC is an important branch of PLC technology due to its low frequency band and low power cost. So far the recent PLC standards, ITU-T G.9903 (G3-PLC) and IEEE 1901.2, are dominating as two of the most robust schemes available. IEEE 1901.2 is a combination of G3-PLC and PRIME while IEEE 1901.2a [[IEEE 1901.2a](#)] is an amendment to IEEE 1901.2. IEEE 1901.1 balances the needs for bandwidth versus communication range, and is thus a promising option for the 6lo applications mentioned above.

[3.1.](#) Protocol Stack

The protocol stack for IPv6 over PLC is illustrated in Figure 1. The PLC MAC/PHY layer corresponds to IEEE 1901.1, IEEE 1901.2 or ITU-T G.9903. The 6lo adaptation layer for PLC is illustrated in [Section 4](#). A routing protocol (e.g., RPL [[RFC6550](#)] or AODV-RPL [[I-D.ietf-roll-aodv-rpl](#)]) at the Network layer is optional according to the IEEE 1901.1 and IEEE 1901.2 PLC standards mentioned in this

document.

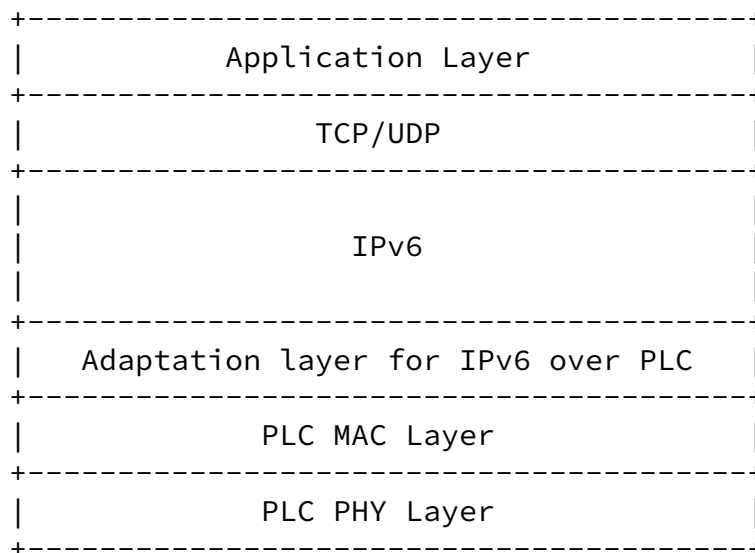


Figure 1: PLC Protocol Stack

[3.2.](#) Addressing Modes

Each PLC device has a globally unique long address of 48-bit ([[IEEE 1901.1](#)]) or 64-bit ([[IEEE 1901.2](#)], [[ITU-T G.9903](#)]) and a short address of 12-bit ([[IEEE 1901.1](#)]) or 16-bit ([[IEEE 1901.2](#)], [[ITU-T G.9903](#)]). The long address is set by the manufacturer

according to the IEEE EUI-48 MAC address or the IEEE EUI-64 address. Each PLC device joins the network by using the long address and communicates with other devices by using the short address after joining the network.

[3.3.](#) Maximum Transmission Unit

The Maximum Transmission Unit (MTU) of the MAC layer determines whether fragmentation and reassembly are needed at the adaptation layer of IPv6 over PLC. IPv6 requires an MTU of 1280 octets or greater; thus for a MAC layer with MTU lower than this limit, fragmentation and reassembly at the adaptation layer are required.

The IEEE 1901.1 MAC supports upper layer packets up to 2031 octets. The IEEE 1901.2 MAC layer supports the MTU of 1576 octets (the

original value of 1280 bytes was updated in 2015 [[IEEE 1901.2a](#)]). Though fragmentation and reassembly are not needed in these two technologies, other 6Lo functions like header compression are still applicable and useful, particularly in high-noise communication environments.

The MTU for ITU-T G.9903 is 400 octets, insufficient for supporting IPv6's MTU. For this reason, fragmentation and reassembly as per [[RFC4944](#)] MUST be enabled for G.9903-based networks.

3.4. Routing Protocol

Routing algorithms suitable for use in PLC networks for AMI applications include:

- o RPL (Routing Protocol for Low-Power and Lossy Networks) [[RFC6550](#)] is a routing protocol (operating at layer 3). AODV-RPL augments RPL to include reactive, point-to-point, and asymmetric routing.
- o ITU-T G.9903 [[ITU-T G.9903](#)] uses LOADng which is a reactive protocol, operating in layer 2 or layer 3.
- o IEEE 1901.1 supports L2 routing, in which the routing entries are built using short addresses.

IEEE 1901.2 specifies additional Information Elements (IEs), with user-defined content, to supply PHY layer metrics for the IP layer. These IEs enable routing protocols to be used in 1901.2 networks. For IPv6-addressable PLC networks, a layer-3 routing protocol such as RPL and/or AODV-RPL SHOULD be supported in the standard. Currently, LOADng is supported in ITU-T G.9903, and the IEEE 1901.2 standard refers to ITU-T G.9903 for LOAD-based networks.

4. IPv6 over PLC

6LoWPAN standards [[RFC4944](#)], [[RFC6775](#)], and [[RFC6282](#)] provides useful functionality including link-local IPv6 addresses, stateless address auto-configuration, neighbor discovery and header compression. However, due to the different characteristics of the PLC media, the 6LoWPAN adaptation layer cannot perfectly fulfill the requirements. Besides, some of the features like fragmentation and reassembly are

redundant to some PLC technologies. Therefore, it is necessary to have a dedicated adaptation layer for PLC, which is detailed in the following subsections.

[4.1.](#) Stateless Address Autoconfiguration

To obtain an IPv6 Interface Identifier (IID), a PLC device performs stateless address autoconfiguration [[RFC4944](#)]. The autoconfiguration can be based on either a long or short link-layer address.

The IID can be based on the device's 48-bit MAC address or its EUI-64 identifier [EUI-64]. A 48-bit MAC address MUST first be extended to a 64-bit Interface ID by inserting 0xFFFE at the fourth and fifth octets as specified in [[RFC2464](#)]. The IPv6 IID is derived from the 64-bit Interface ID by inverting the U/L bit [[RFC4291](#)].

For IEEE 1901.2 and ITU-T G.9903, a 48-bit "pseudo-address" is formed by the 16-bit PAN ID, 16 zero bits and the 16-bit short address. Then, the 64-bit Interface ID MUST be derived by inserting 16-bit 0xFFFE into as follows:

16_bit_PAN:00FF:FE00:16_bit_short_address

For the 12-bit short addresses used by IEEE 1901.1, the 48-bit pseudo-address is formed by 24-bit NID (Network Identifier, YYYYYY), 12 zero bits and a 12-bit TEI (Terminal Equipment Identifier, XXX). The 64-bit Interface ID MUST be derived by inserting 16-bit 0xFFFE into this 48-bit pseudo-address as follows:

YYYY:YYFF:FE00:0XXX

Since the derived Interface ID is not global, the "Universal/Local" (U/L) bit (7th bit) and the Individual/Group bit (8th bit) MUST both be set to zero. In order to avoid any ambiguity in the derived Interface ID, these two bits MUST NOT be used to generate the PANID (for IEEE 1901.2 and ITU-T G.9903) or NID (for IEEE 1901.1). In other words, the PANID or NID MUST always be chosen so that these bits are zeros.

[4.2.](#) IPv6 Link Local Address

The IPv6 link-local address [RFC4291] for a PLC interface is formed by appending the IID, as defined above, to the prefix FE80::/64 (see Figure 2).

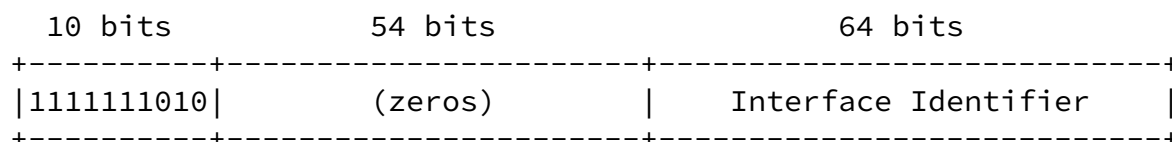


Figure 2: IPv6 Link Local Address for a PLC interface

4.3. Unicast Address Mapping

The address resolution procedure for mapping IPv6 unicast addresses into PLC link-layer addresses follows the general description in [section 7.2 of \[RFC4861\]](#). [RFC6775] improves this procedure by eliminating usage of multicast NS. The resolution is realized by the NCEs (neighbor cache entry) created during the address registration at the routers. 6775-update further improves the registration procedure by enabling multiple LLNs to form an IPv6 subnet, and by inserting a link-local address registration to better serve proxy registration of new devices.

4.3.1. Unicast Address Mapping for IEEE 1901.1

The Source/Target Link-layer Address options for IEEE_1901.1 used in the Neighbor Solicitation and Neighbor Advertisement have the following form.

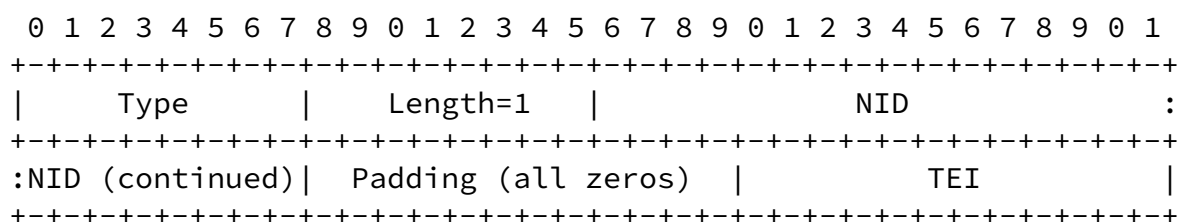


Figure 3: Unicast Address Mapping for IEEE 1901.1

Option fields:

Type: 1 for Source Link-layer Address and 2 for Target Link-layer Address.

Length: The length of this option (including type and length fields) in units of 8 octets. The value of this field is 1 for the 12-bit IEEE 1901.1 PLC short addresses.

NID: 24-bit Network IDentifier

Padding: 12 zero bits

TEI: 12-bit Terminal Equipment Identifier

In order to avoid the possibility of duplicated IPv6 addresses, the value of the NID MUST be chosen so that the 7th and 8th bits of the first byte of the NID are both zero.

[4.3.2.](#) Unicast Address Mapping for IEEE 1901.2 and ITU-T G.9903

The Source/Target Link-layer Address options for IEEE_1901.2 and ITU-T G.9903 used in the Neighbor Solicitation and Neighbor Advertisement have the following form.

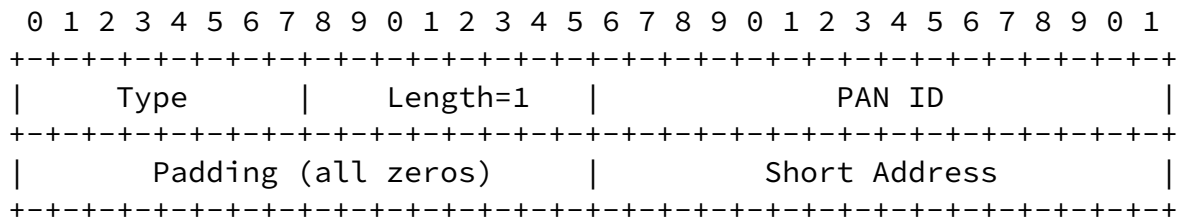


Figure 4: Unicast Address Mapping for IEEE 1901.2

Option fields:

Type: 1 for Source Link-layer Address and 2 for Target Link-layer Address.

Length: The length of this option (including type and length fields) in units of 8 octets. The value of this field is 1 for the 16-bit IEEE 1901.2 PLC short addresses.

PAN ID: 16-bit PAN IDentifier

Padding: 16 zero bits

Short Address: 16-bit short address

In order to avoid the possibility of duplicated IPv6 addresses, the value of the PAN ID MUST be chosen so that the 7th and 8th bits of the first byte of the PAN ID are both zero.

[4.4.](#) Neighbor Discovery

Neighbor discovery procedures for 6LoWPAN networks are described in Neighbor Discovery Optimization for 6LoWPANs [[RFC6775](#)] and [[I-D.ietf-6lo-rfc6775-update](#)]. These optimizations support the registration of sleeping hosts. Although PLC devices are electrically powered, sleeping mode SHOULD still be used for power saving.

[RFC6775](#)-only [[RFC6775](#)] PLC devices follow Sections [5.3](#) and [5.4](#) of that specification for sending Router Solicitations and processing Router Advertisements to acquire the IPv6 prefix and context information. Such a PLC host MUST register its address to the router using Neighbor Solicitation and Neighbor Advertisement messages. In addition, if DHCPv6 is used to assign addresses, or the IPv6 address is derived by unique long or short link layer address, Duplicate Address Detection (DAD) MUST NOT be utilized.

[RFC6775](#)-update [[I-D.ietf-6lo-rfc6775-update](#)] PLC devices include the EARO with the 'R' flag set when sending Router Solicitations, and process Router Advertisements that include EARO to extract status information. Duplicate Address Detection is in this case proxied by a routing registrar, which MAY operate according to Optimistic DAD (ODAD) [[RFC4429](#)]. For networks with mixed [RFC6775](#)-only and [RFC6775](#)-update devices, the [RFC6775](#)-update PLC devices MUST use a 64-bit ROVR.

If the PLC network uses route-over mesh, the IPv6 prefix MAY be disseminated by the layer 3 routing protocol, such as RPL which includes the prefix in the DIO message. The prefix information option (PIO) MUST NOT be included in the Router Advertisement.

The mesh-under ITU-T G.9903 network SHOULD NOT utilize the address registration as described in [[RFC6775](#)]. ITU-T G.9903 PLC networks MUST use the 6LoWPAN Context Option (6CO) specified in [[RFC6775](#)] (see clause 9.4.1.1 in [[ITU-T G.9903](#)]), which can be attached in Router Advertisements to disseminate Context IDs (CIDs) to use for compressing prefixes. An implementation for mesh-under operation MUST use [[RFC6775](#)] mechanisms for managing IPv6 prefixes and

corresponding header compression context information [[RFC6282](#)].

[4.5.](#) Header Compression

The compression of IPv6 datagrams within PLC MAC frames refers to [[RFC6282](#)], which updates [[RFC4944](#)]. Header compression as defined in [[RFC6282](#)] which specifies the compression format for IPv6 datagrams on top of IEEE 802.15.4, is included in this document as the basis for IPv6 header compression in PLC. For situations when PLC MAC MTU

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cannot support the 1280-octet IPv6 packet, headers MUST be compressed according to [[RFC6282](#)] encoding formats.

[4.6.](#) Fragmentation and Reassembly

PLC differs from other wired technologies in that the communication medium is not shielded; thus, to successfully transmit data through power lines, PLC Data Link layer provides the function of segmentation and reassembly. A Segment Control Field is defined in the MAC frame header regardless of whether segmentation is required. The number of data octets of the PHY payload can change dynamically based on channel conditions, thus the MAC payload segmentation in the MAC sublayer is enabled and guarantees a reliable one-hop data transmission.

In IEEE 1901.1 and IEEE 1901.2, since the MAC layer supports a payload of respectively 2031 octets and 1576 octets, which is larger than the minimum MTU required by IPv6 packets, there is no need of fragmentation for the IPv6 packet transmission, thus the fragmentation and reassembly defined in [[RFC4944](#)] MUST NOT be used in the 6lo adaptation layer of IEEE 1901.2.

In ITU-T G.9903, the maximum MAC payload size is fixed to 400 octets, so to cope with the required MTU of 1280 octets by IPv6, fragmentation and reassembly at 6lo adaptation layer MUST be provided referring to [[RFC4944](#)].

[4.7.](#) Extension at 6lo Adaptation Layer

Apart from the Dispatch and LOWPAN_IPHC headers specified in [[RFC4944](#)], an additional Command Frame Header is needed for the mesh routing procedure in LOADng protocol. Figure 5 illustrates the

format of the Command Frame Header [[RFC8066](#)]. The ESC dispatch type (01000000b) indicates an ESC extension type follows (see [[RFC4944](#)] and [[RFC6282](#)]). Then this 1-octet dispatch field is used as the Command Frame Header and filled with the Command ID. The Command ID can be classified into 4 types:

- o LOADng message (0x01)
- o LoWPAN bootstrapping protocol message (0x02)
- o Reserved by ITU-T (0x03-0x0F)
- o CMSR protocol messages (0x10-0x1F)

The LOADng message is used to provide the default routing protocol LOADng while the LoWPAN bootstrapping protocol message is for the

LoWPAN bootstrap procedure. The CMSR protocol messages are specified for the Centralized metric-based source routing [ITU-T G.9905] which is out of the scope of this draft.

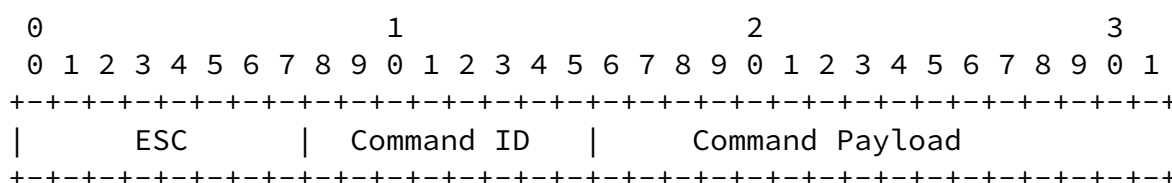


Figure 5: Command Frame Header Format of ITU-T G.9903

Command Frame Header appears in the last position if more than one header is present in the 6LoWPAN frame [[ITU-T G.9903](#)]. On the other hand, this Command Frame Header MUST appear before the LoWPAN_IPHC dispatch type as per[RFC8066].

- o Regarding the order of the command frame header, the inconsistency between G.9903 and [RFC8066](#) still exists and is being solved in ITU-T SG15/Q15.

Following these two requirements of header order mentioned above, an example of the header order is illustrated in Figure 6 including the Fragmentation type, Fragmentation header, ESC dispatch type, ESC Extension Type (Command ID), ESC Dispatch Payload (Command Payload),

LOWPAN_IPHC Dispatch Type, LOWPAN_IPHC header, and Payload.

```

+-----+-----+-----+-----+-----+-----+-----+-----+
|F typ|F hdr| ESC | EET | EDP |Dispatch|LOWPAN_IPHC hdr| Payld|
+-----+-----+-----+-----+-----+-----+-----+-----+

```

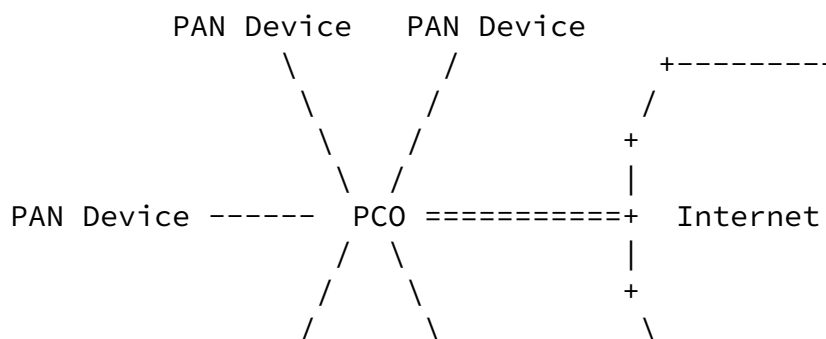
Figure 6: A 6LoWPAN packet including the Command Frame Header

5. Internet Connectivity Scenarios and Topologies

The network model can be simplified to two kinds of network devices: PAN Coordinator (PCO) and PAN Device. The PCO is the coordinator of the PLC subnet and can be seen as a master node; PAN Devices are typically PLC meters and sensors. The PCO also serves as the Routing Registrar for proxy registration and DAD procedures, making use of the updated registration procedures in [[I-D.ietf-6lo-rfc6775-update](#)]. IPv6 over PLC networks are built as tree, mesh or star according to the use cases. Every network requires at least one PCO to communicate with each PAN Device. Note that the PLC topologies in this section are based on logical connectivity, not physical links.

The star topology is common in current PLC scenarios. In star topologies, communication at the link layer only takes place between

a PAN Device and a PCO. The PCO typically collects data (e.g. smart meter reading) from the PAN devices, and then concentrates and uploads the data through Ethernet or LPWAN (see Figure 7). The collected data is transmitted by the smart meters through PLC, aggregated by a concentrator, sent to the utility and then to a Meter Data Management System for data storage, analysis and billing. This topology has been widely applied in the deployment of smart meters, especially in apartment buildings.





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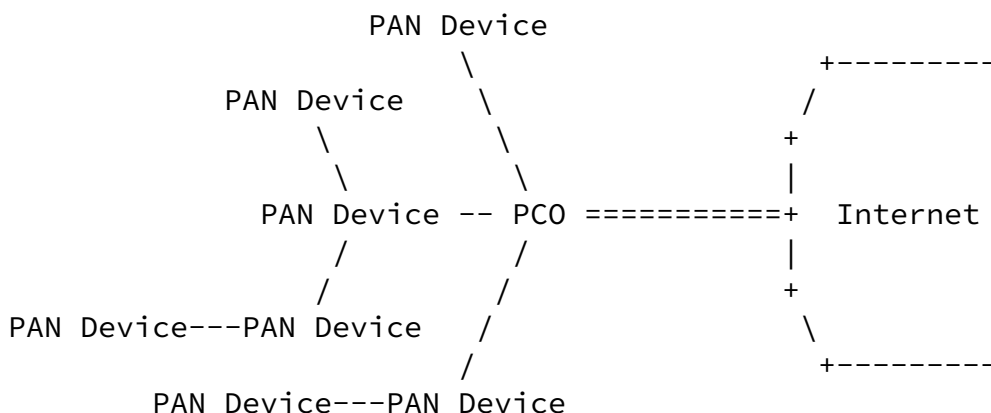
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 PLC subnet (IPv6 over PLC)

Figure 8: PLC Tree Network connected to the Internet

Mesh networking in PLC is of great potential applications and has been studied for several years. By connecting all nodes with their neighbors in communication range (see Figure 9), mesh topology dramatically enhances the communication efficiency and thus expands the size of PLC networks. A simple use case is the smart home scenario where the ON/OFF state of air conditioning is controlled by the state of home lights (ON/OFF) and doors (OPEN/CLOSE). AODV-RPL enables direct PAN device to PAN devices (without being obliged to transmit frames through the PCO). This significantly improves performance in typical use cases, like charging station to electric vehicle (EV) communications.

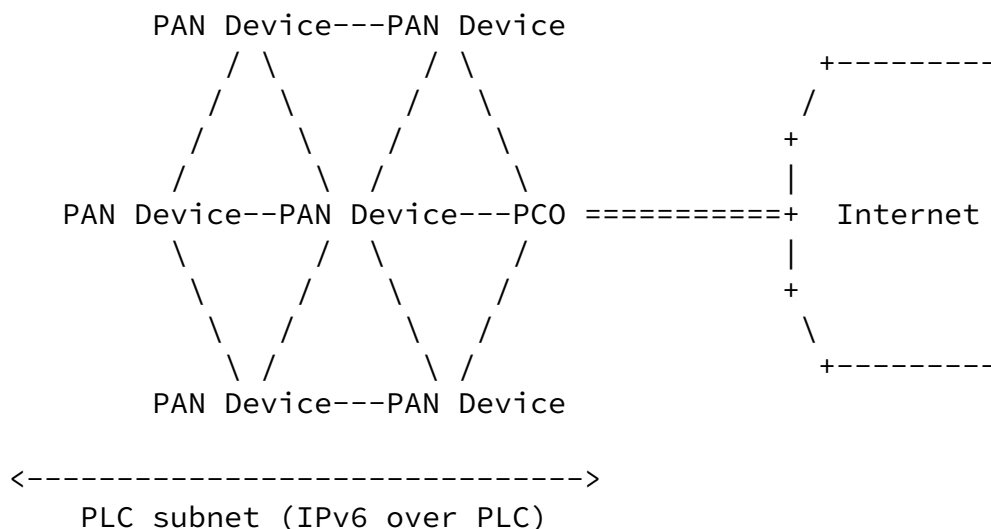


Figure 9: PLC Mesh Network connected to the Internet

6. IANA Considerations

There are no IANA considerations related to this document.

7. Security Consideration

Due to the high accessibility of power grid, PLC might be susceptible to eavesdropping within its communication coverage, e.g. one apartment tenant may have the chance to monitor the other smart meters in the same apartment building. For security consideration, link layer security is guaranteed in every PLC technology.

IP addresses may be used to track devices on the Internet; such devices can in turn be linked to individuals and their activities. Depending on the application and the actual use pattern, this may be undesirable. To impede tracking, globally unique and non-changing characteristics of IP addresses should be avoided, e.g., by frequently changing the global prefix and avoiding unique link-layer derived IIDs in addresses. [\[RFC3315\]](#), [\[RFC3972\]](#), [\[RFC4941\]](#), [\[RFC5535\]](#), [\[RFC7217\]](#), and [\[RFC8065\]](#) provide valuable information for IID formation with improved privacy, and are RECOMMENDED for IPv6 networks.

8. Acknowledgements

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