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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 the smart meters for electricity. With the inherent advantage of existing electricity infrastructure, PLC is expanding deployments all over the world, indicating the potential demand of IPv6 for future applications. As part of this technology, Narrowband PLC (NBPLC) is focused on the low-bandwidth and low-power scenarios, including current standards such as IEEE 1901.2 and ITU-T G.9903. This document describes how IPv6 packets are transported over constrained PLC networks.

Status of this Memo

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Table of Contents

1. Introduction

The idea of using power line for both electricity supply and communication can be traced back to the beginning of the last century. With the obvious advantage of existing power grid, 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 the common features like fixed position, large quantity, low data rate, and long life time.

Although PLC technology has an evolution history of several decades, the adaptation of PLC for IP based constrained networks is not fully developed. The 6lo related scenarios lie in the low voltage PLC networks with most applications in the area of Advanced Metering Infrastructure, Vehicle-to-Grid communications, in-home energy management and smart street lighting. It is of great importance to deploy IPv6 for PLC devices for its large address space and quick addressing. In addition, due to various existing PLC standards, a comparison among them is needed to facilitate the selection of the most applicable PLC standard in certain using 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. Similar 6LoPLC adaptation layer was previously proposed in [draft-popa-6lo-6loplc], however, with the same purpose, this document provides more updated, structured and instructive information for the deployment of IPv6 over PLC 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].

Below are the terms used in this document:

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

AMI: Advanced Metering Infrastructure

BBPLC: Broadband Power Line Communication

BR: Border Router

HDPLC: High Definition Power Line Communication

IID: Interface Identifier

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

PLC: Power Line Communication

PSDU: PHY Service Data Unit

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

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 its 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. IEEE 1901 and ITU-T G.hn for BBPLC (1.8-250 MHz), IEEE 1901.2, ITU-T G.9902 (G.hnem), ITU-T G.9903 (G3-PLC) and ITU-T G.9904 (PRIME) for NBPLC (3-500 kHz) and the recent proposal for the IEEE 1901.1 standard aiming at the frequency band of 2-12 MHz.

Narrowband PLC is a very 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. Different networking methods exist in different NBPLC standards. The formation of a ITU-T G.9903 network is based on a MAC Layer routing protocol called LOADng (Lightweight On-demand Ad-hoc Distance-vector Routing Protocol Next Generation). Different from ITU-T G.9903, IEEE 1901.2 enables a variable structure of the MAC layer which can alternatively apply layer-2 or layer-3 mesh networking. IEEE 1901.2 enables a coexistence mode with ITU-T G.9903 using layer-2 LOADng protocol, and on the other hand it allows the adaptation of layer-3 RPL protocol (IPv6 Routing Protocol for Low-Power and Lossy Networks).

The IEEE 1901.1 WG is currently working on a new PLC standard, IEEE 1901.1, which focuses on the frequency band of 2-12 MHz [IEEE 1901.1]. This promising medium-frequency PLC standard, known as PLC-IOT, is suitable for 6lo applications thus mentioned in this document. Details on this standard is to be determined.

3.1. Protocol Stack

The protocol stack for IPv6 over PLC is illustrated in Figure 1 that contains the following elements from bottom to top: PLC PHY Layer, PLC MAC Layer, Adaptation layer for IPv6 over PLC, IPv6 Layer, TCP/UDP Layer and Application Layer. The PLC MAC/PHY layer corresponds to a certain PLC standard such as IEEE 1901.2 or ITU-T G.9903. For the Broadband PLC cases, the adaptation layer for IPv6 over PLC MAY not be used unless in some certain specifications. The deployment of the 6lo adaptation layer are specified in section 4 according to different standards. Routing protocol like RPL on Network layer is optional according to the specified PLC standard, for example IEEE 1901.2 MAY use RPL protocol while ITU-T G.9903 MUST NOT.

```
+-----------------------------------------+
|            Application Layer            |
+-----------------------------------------+
|                 TCP/UDP                 |
+-----------------------------------------+
|                                         |
|                  IPv6                   |
|                                         |
|-----------------------------------------|
|   Adaptation layer for IPv6 over PLC    |
+-----------------------------------------+
|              PLC MAC Layer              |
|   (IEEE 1901.2 MAC/ITU-T G.9903 MAC)    |
+-----------------------------------------+
|              PLC PHY Layer              |
|   (IEEE 1901.2 PHY/ITU-T G.9903 PHY)    |
+-----------------------------------------+
```

Figure 1: PLC Protocol Stack

3.2. Addressing Modes

Two addressing modes are enabled in PLC including the IEEE 64-bit extended address and the 16-bit short address which is unique within the PAN [IEEE 1901.2, ITU-T G.9903]. Physical addressing uses a globally unique 64-bit address to represent each node on the powerline. This is useful when initializing a system because the

nodes do not have unique logical addresses on power up. Logical addressing uses 16-bit short address to represent each node on the powerline with a much lower latency and higher throughput. Note that in ITU-T G.9930, though two addressing modes are enabled, only 16-bit addressing is supported in mesh routing.

3.3. Maximum Transmission Unit

Maximum Transmission Unit (MTU) of MAC layer is an important parameter that determines the applicability of fragmentation and reassembly at the adaptation layer of IPv6 over PLC. IPv6 requires that every link in the Internet have 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.

As a wired communication technology, the MTU of PLC MAC layer is normally higher than wireless technology based on IEEE 802.15.4. The IEEE 1901.2 MAC layer supports the MTU of 1576 octets (the original value 1280 byte was updated in 2015 [IEEE 1901.2a]). The MTU for ITU-T G.9903 is 400 octets, insufficient for supporting complete IPv6 packets. For this concern, fragmentation/reassembly in [RFC 4944] MUST be enabled for the G.9903-based scenarios (details can be found in section 4.2.5).

4. Specification of IPv6 over Narrowband PLC

Due to the narrow bandwidth and low data rate in NBPLC, a 6lo adaptation layer is needed to support the transmission of IPv6 packets. 6LoWPAN standards [RFC 4944], [RFC 6775], and [RFC 6282] provides useful functionality including link-local IPv6 addresses, stateless address auto-configuration, neighbor discovery and header compression. These standards are referred in the specifications of the 6lo adaptation layer which is illustrated in the following subsections.

4.1. IEEE 1901.2

4.1.1. Stateless Address Autoconfiguration

An IEEE 1901.2 device performs stateless address autoconfiguration according to [RFC 4944] so as to obtain an IPv6 Interface Identifier (IID). In the 16-bit short addressing mode, the 64-bit IID SHALL be derived by insert 16-bit "FFEE" into a "pseudo 48-bit address" which is formed by the 16-bit PAN ID, 16-bit zero and the 16-bit short address as follows:

```
16_bit_PAN:00FF:FE00:16_bit_short_address
```

Considering that this derived IID is not globally unique, the "Universal/Local" (U/L) bit (7th bit) SHALL be set to zero.

For the EUI-64 addressing mode, as per [RFC 2464], the Interface Identifier is then formed from by complementing the U/L bit, generally setting to 1, since an interface's built-in address is expected to be globally unique.

4.1.2. IPv6 Link Local Address

The IPv6 link-local address [RFC4291] for an IEEE 1901.2 interface is formed by appending the Interface Identifier, as defined above, to the prefix FE80::/64 (see Figure 2).

```
  10 bits            54 bits                  64 bits
+----------+-----------------------+----------------------------+
|1111111010|        (zeros)        |    Interface Identifier    |
+----------+-----------------------+----------------------------+
```

Figure 2: IPv6 Link Local Address in IEEE 1901.2

4.1.3. Unicast and Multicast Address Mapping

The address resolution procedure for mapping IPv6 unicast addresses into IEEE 1901.2 link-layer addresses follows the general description in section 7.2 of [RFC4861], unless otherwise specified.

The Source/Target Link-layer Address option has the following forms when the link layer is IEEE 1901.2 and the addresses are EUI-64 or 16-bit short addresses, respectively.

```
 0                   1                 0                   1
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5   0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+ +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     Type      |    Length=2   | |     Type      |    Length=1   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+ +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                               | |     16-bit short Address      |
+-         IEEE 1901.2         -+ +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|            EUI-64             | |           Padding             |
+-                             -+ +-                             -+
|                               | |         (all zeros)           |
+-           Address           -+ +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                               |
+-           Padding           -+
|                               |
+-         (all zeros)         -+
|                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 3: Unicast Address Mapping in IEEE 1901.2

Option fields:

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

Length: This is the length of this option (including the type and length fields) in units of 8 octets. The value of this field is 2 if using EUI-64 addresses, or 1 if using 16-bit short addresses.

IEEE 1901.2 Address: The 64-bit IEEE 1901.2 address, or the 16-bit short address. This is the address the interface currently responds to. This address may be different from the built-in address used to derive the Interface Identifier, because of privacy or security (e.g., of neighbor discovery) considerations.

Multicast address mapping is not supported in IEEE 1901.2. A link-local multicast only reaches neighbors within direct physical connectivity. IEEE 1901.2 excludes the functionality of multicast either in [RFC 4944] or in coexistence modes with G3-PLC and PRIME. However, IEEE 1901.2 supports the required MTU by IPv6, eliminating the need of fragmentation and reassembly at the 6lo adaptation layer, so the multicast functionality in this case is applicable and is RECOMMENDED in this document.

4.1.4. Header Compression

The IEEE 1901.2 PHY layer supports a maximum PSDU (PHY Service Data Unit) of 512 octets while the allowed PHY payload is smaller and can change dynamically based on channel conditions. Due to the limited PHY payload, header compression at 6lo adaptation layer is of great importance and MUST be applied. The compression of IPv6 datagrams within IEEE 1901.2 frames refers to [RFC 6282], which updates [RFC 4944]. Header compression as defined in RFC6282 which specifies the fragmentation methods for IPv6 datagrams on top of IEEE 802.15.4, is REQUIRED in this document as the basis for IPv6 header compression in IEEE 1901.2. All headers MUST be compressed according to RFC6282 encoding formats.

4.1.5. Fragmentation and Reassembly

To cope with the mismatch between the size of the PHY frame payload and the size of the MAC Service Data Unit (MSDU), IEEE 1901.2 MAC layer provides the functionality of segmentation and reassembly. A Segment Control Field is defined in the MAC frame header regardless of whether segmentation is required. This process segments a MAC layer datagram into multiple fragments and provides a reliable one-hop transfer of the resulting fragments. However, for the 6lo adaptation layer, since IEEE 1901.2 naturally supports a MAC payload of 1280 octets, the minimum MTU of IPv6, there is no need for fragmentation and reassembly for the IPv6 packet transmission. This document specifies that, in the IPv6 packet transmission over IEEE 1901.2, fragmentation and reassembly in [RFC 4944] MUST NOT be used.

4.2. ITU-T G.9903

4.2.1. Stateless Address Autoconfiguration

The stateless address auto-configuration in ITU-T G.9903 also refers to [RFC 4944] with the following selections: The 64-bit interface identifier shall be derived from a "pseudo 48-bit address" formed with the PAN identifier and the short address as follows: 0xYYYY:00FF:FE00:XXXX where 0xYYYY is the PAN identifier and XXXX is the short address. Additional care shall be taken when choosing a PAN identifier so as not to interfere with I/G and U/L bits of the interface identifier. If the PAN identifiers are chosen randomly, then the U/L and I/G bits (7th and 8th bits) shall be set to zero [ITU-T G.9903].

4.2.2. IPv6 Link Local Address

In ITU-T G.9903, the formation of IPv6 link-local address follows the same process as IEEE 1901.2 (see section 4.1.2) by appending the Interface Identifier (IID) to the prefix FE80::/64.

4.2.3. Unicast and Multicast Address Mapping

The address resolution procedure for mapping IPv6 unicast addresses into ITU-T G.9903 link-layer addresses follows the general description in section 7.2 of [RFC4861], unless otherwise specified. Source/Target link-layer address option field SHOULD contain the EUI-64 address or the combined address with PAN ID and 16-bit short address of the source or target device as below. Note that the format of the Target Link-layer address in ITU-T G.9903 (see Figure 4) is specified according to the Annex E of [ITU-T G.9903].

```
 0                   1               0                   1
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5    0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     Type      |    Length=2   |  |     Type      |    Length=1   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                               |  |            PAN ID             |
+-         ITU-T G.9903        -+  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|             EUI-64            |  |     16-bit short Address      |
+-                             -+  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|             Address           |  |         (all zeros)           |
+-                             -+  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                               |
+-            Padding          -+
|                               |
+-          (all zeros)        -+
|                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 4: Unicast Address Mapping in ITU-T G.9903

Option fields:

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

Length: This is the length of this option (including the type and length fields) in units of 8 octets. The value of this field is 2 if using EUI-64 addresses, or 1 if using 16-bit short addresses.

ITU-T G.9903 Address: The 64-bit IEEE 1901.2 address, or the 16-bit short address. This is the address the interface currently responds to. This address may be different from the built-in address used to derive the Interface Identifier, because of privacy or security (e.g., of neighbor discovery) considerations.

The address resolution procedure for mapping IPv6 multicast addresses into ITU-T G.9903 link-layer addresses follows the general description in [RFC 4944] and MUST only be used in a mesh-enabled network. An IPv6 packet with a multicast destination address (DST), consisting of the sixteen octets DST[1] through DST[16], is transmitted to the following 802.15.4 16-bit multicast address (see Figure 5):

```
  0                   1
  0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |1 0 0|DST[15]* |    DST[16]    |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 5: Multicast Address Mapping

Here, DST[15]* refers to the last 5 bits in octet DST[15], that is, bits 3-7 within DST[15]. The initial 3-bit pattern of "100" follows the 16-bit address format for multicast addresses (see Section 12 of [RFC 4944]).

4.2.4. Header Compression

Header compression as defined in [RFC6282], which specifies the compression format for IPv6 datagrams on top of IEEE 802.15.4, is REQUIRED in this document as the basis for IPv6 header compression in ITU-T G.9903. All headers MUST be compressed according to [RFC6282] encoding formats.

4.2.5. Fragmentation and Reassembly

Similar to IEEE 1901.2, Segment Control Field is also defined in the ITU-T G.9903 MAC frame header, and the functionality of fragmentation and reassembly is also enabled at the G.9903 MAC layer. However, the maximum MAC payload size is fixed to 400 octets at the present ITU-T G.9903 recommendation, thus to cope with the required MTU of 1280 octets by IPv6, fragmentation and reassembly at 6lo adaptation layer MUST be provided referring to [RFC 4944].

To avoid the duplicate fragmentation at both 6lo adaptation layer and ITU-T G.9903 MAC layer, an optional way is to limit the MAC payload size so that the MSDU can fit the PHY payload without MAC layer fragmentation. However, the number of data bytes of the PHY payload can change dynamically based on channel conditions (see section 9.3 in [ITU-T G.9903]), so the best solution is incrementing the allowed MAC payload size above 1280 octets so as to avoid the use of fragmentation and reassembly at 6lo adaptation layer.

4.2.6. Extension at 6lo Adaptation Layer

Apart from the 6Lo headers specified in [RFC 4944], an additional command frame header is defined for the mesh routing procedure which appears in the following order: Mesh addressing header, Broadcast header, Fragmentation header, Command frame header [ITU-T G.9903].

Figure 6 shows an example of the command frame: The ESC header type (01000000b) indicates an additional dispatch byte follows (see [RFC 4944] and [RFC 6282]). Then this 1-octet dispatch field is used as the Command frame header and filled with the Command ID. This header shall be in the last position if more than one header is present in the frame. The Command ID can be classified into 4 types:

- LOADng message (0x01)

- LoWPAN bootstrapping protocol message (0x02)

- Reserved by ITU-T (0x03-0x0F)

- CMSR protocol messages (0X10-0X1F)

```
          0                   1                   2
     Bits 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3
         +---------------+---------------+-----------------
         |ESC header type|               |
         |               |   Command ID  | Command Payload
         |  01 000000b   |               |
         +---------------+---------------+-----------------
```

Figure 6: Command Frame Header Format of ITU-T G.9903

For the Mesh addressing type and header, it is worthy to note that the value of the HopsLeft field SHALL not exceed adpMaxHops. When the originator and final destination devices are neighbors (i.e., the next hop address equals the final destination address and the next hop address is present in the originator's neighbor table), the mesh header shall be omitted in the frame.

5. Internet Connectivity Scenarios and Topologies

The network model can be simplified to two kinds of network devices: Border Router (BR) and Node. BR is the coordinator of the PLC subnet and can be seen as a master node while Nodes are typically PLC meters and sensors. The IPv6 over PLC networks SHOULD be built as tree, mesh or star according to the specified using scenarios. Every network requires at least one BR to communicate with each nodes.

One common topology in the current PLC scenarios is star. In this case, the communication at the link layer only takes place between a node and a BR. The BR collects data (e.g. smart meter reading) from different nodes, 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.

```
               Node      Node
                 \        /           +---------
                  \      /           /
                   \    /           +
                    \  /            |
        Node ------  BR =========== |  Internet
                    /  \            |
                   /    \           +
                  /      \           \
                 /        \           +---------
               Node      Node

        <----------------------->
              PLC subnet
```

Figure 7: PLC Star Network connected to the Internet

Tree topology is used when the distance between a node A and BR is beyond the PLC allowed limit while there is another node B in between able to communicate with both sides. Node B in this case acts both as a 6lo Node and a Proxy Coordinator (PCO). For this scenario, the link layer communications take place between node A and node B, and between node B and BR. An example of PLC tree network is depicted in Figure 8. This topology can be applied in the smart street lighting, where the lights adjust the brightness to reduce energy consumption while sensors are deployed on the street lights to give information such as wind speed, temperature, humidity. Data transmission distance in the street lighting scenario is normally above several kilometers thus the PLC tree network is required. A more sophisticated AMI network may also be constructed into the tree topology which as depicted in [RFC 8036].

```
                       Node
                         \                  +---------
               Node       \                /
                 \         \              +
                  \         \             |
         Node --- Node ----- BR ========== |  Internet
                  /         /             |
                 /         /              +
      Node --- Node       /                \
                         /                  +---------
              Node --- Node

      <-------------------------->
               PLC subnet
```

Figure 8: PLC Tree Network connected to the Internet

Mesh networking in PLC is still under development but of great potential applications. 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 a PLC network. 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).

```
               Node ----- Node
               / \        / \                +---------
              /   \      /   \              /
             /     \    /     \            +
            /       \  /       \           |
   Node --- Node ---- Node ----- BR =========== |  Internet
            \       /  \       /           |
             \     /    \     /            +
              \   /      \   /              \
               \ /        \ /                +---------
               Node ----- Node

   <---------------------------------->
              PLC subnet
```

Figure 9: PLC Mesh Network connected to the Internet

6. IANA Considerations

There are no IANA considerations related to this document.

7. Security Consideration

This document has no security consideration beyond those in [RFC 4944] and [RFC 6282].

8. References

8.1. Normative References

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