Transmission of IPv6 Packets over PLC Networks
draft-ietf-6lo-plc-00

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 and IEEE 1901.2.

Status of This Memo

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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).
The data acquisition devices in these scenarios share common features
such as fixed position, large quantity, low data rate and low power
consumption.

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 efficent address auto-configuration. A
comparison among various existing PLC standards is provided to
facilitate the selection of the most applicable standard in
particular scenarios.

This specification provides a brief overview of PLC technologies.
Some of them have LLN characteristics, i.e. limited power
consumption, memory and processing resources. This specification is
focused on the transmission of IPv6 packets over those "constrained"
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 and terminologies:

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

AMI: Advanced Metering Infrastructure

BBPLC: Broadband Power Line Communication

CID: Context ID

Coordinator: A device capable of relaying messages.

DAD: Duplicate Address Detection

PAN device: An entity follows the PLC standards and implements the
      protocol stack described in this draft.

EV: Electric Vehicle

IID: IPv6 Interface Identifier

IPHC: IP Header Compression

LAN: Local Area Network

MSDU: MAC Service Data Unit

MTU: Maximum Transmission Unit

NBPLC: Narrowband Power Line Communication

OFDM: Orthogonal Frequency Division Multiplexing

PANC: PAN Coordinator, a coordinator which also acts as the primary
      controller of a PAN.

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

The terminology used in this draft is aligned with IEEE 1901.2

```
+-----------------+--------------------+---------------------+
|   IEEE 1901.2   |    IEEE 1901.1     |    ITU-T G.9903     |
+-----------------+--------------------+---------------------+
| PAN Coordinator | Central Coordinator|   PAN Coordinator   |
|                 |                    |                     |
|   Coordinator   |  Proxy Coordinator | Full-function device|
|                 |                    |                     |
|     Device      |      Station       |     PAN Device      |
+-----------------+--------------------+---------------------+
```

Table 1: Terminology Mapping between PLC standards

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
(which have low frequency band and low power cost), 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 ITU-T G.9902
(G.hnem), ITU-T G.9903 (G3-PLC) [ITU-T_G.9903], ITU-T G.9904 (PRIME),
IEEE 1901.2 [IEEE_1901.2] (combination of G3-PLC and PRIME PLC) and
IEEE 1901.2a [IEEE_1901.2a] (an amendment to IEEE 1901.2). 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). IEEE 1901.1 balances the needs for bandwidth versus
communication range, and is thus a promising option for 6lo
applications. Currently, this specification is focused on IEEE
1901.1, IEEE 1901.2 and ITU-T G.9903.

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. For multihop tree and mesh topologies, a routing protocol
is likely to be necessary. The routes can be built in mesh-under
mode at layer 2 or in route-over mode at layer 3.

```
            +----------------------------------------+
            |            Application Layer            |
            +----------------------------------------+
            |                TCP/UDP                  |
            +----------------------------------------+
            |                                        |
            |                 IPv6                   |
            |                                        |
            +----------------------------------------+
            |    Adaptation layer for IPv6 over PLC   |
            +----------------------------------------+
            |              PLC MAC Layer              |
            +----------------------------------------+
            |              PLC PHY Layer              |
            +----------------------------------------+
```
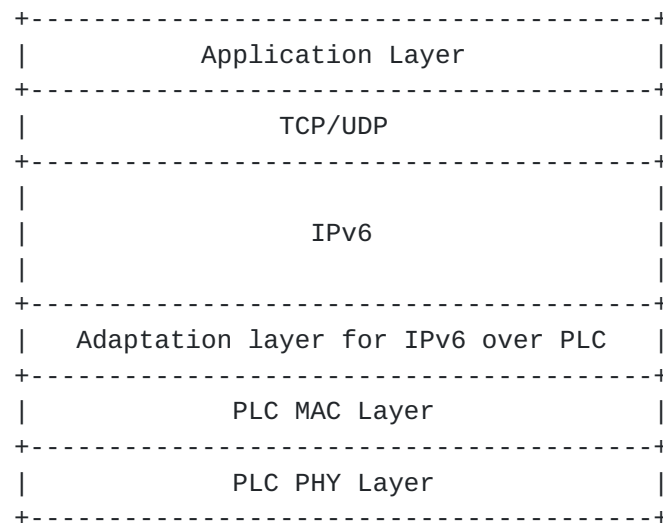
Figure 1: PLC Protocol Stack

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 protocols suitable for use in PLC networks include:

o RPL (Routing Protocol for Low-Power and Lossy Networks) [RFC6550]
   is a layer 3 routing protocol. AODV-RPL [I-D.ietf-roll-aodv-rpl]
   updates RPL to include reactive, point-to-point, and asymmetric
   routing. IEEE 1901.2 specifies Information Elements (IEs) with
   MAC layer metrics, which can be provided to L3 routing protocol
   for parent selection. For IPv6-addressable PLC networks, a
   layer-3 routing protocol such as RPL and/or AODV-RPL SHOULD be
   supported in the standard.

o IEEE 1901.1 supports L2 routing. Each PLC node maintains a L2
   routing table, in which each route entry comprises the short
   addresses of the destination and the related next hop. The route
   entries are built during the network establishment via a pair of
   association request/confirmation messages. The route entries can
   be changed via a pair of proxy change request/confirmation
   messages. These association and proxy change messages MUST be
   approved by the central coordinator.

o LOADng is a reactive protocol operating at layer 2 or layer 3.
   Currently, LOADng is supported in ITU-T G.9903 [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
redudant to some PLC technologies. These considerations suggest the
need for 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.

For privacy reasons, the IID derived by the MAC address SHOULD only
be used for link-local address configuration. A PLC host SHOULD use
the IID derived by the link-layer short address to configure the IPv6
address used for communication with the public network; otherwise,
the host's MAC address is exposed.

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).

```
   10 bits            54 bits                   64 bits
  +----------+----------------------+---------------------------+
  |1111111010|       (zeros)        |    Interface Identifier   |
  +----------+----------------------+---------------------------+
```
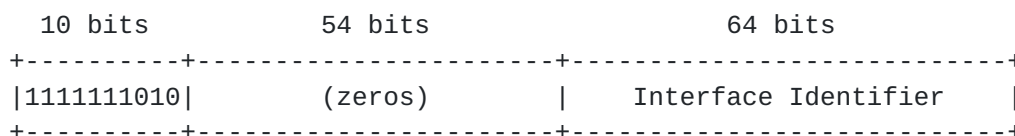
        Figure 2: IPv6 Link Local Address for a PLC interface

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.

```
   0                   1                   2                   3
   0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
  |     Type      |   Length=1    |             NID               :
  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
  :NID (continued)|  Padding (all zeros)  |          TEI          |
  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

          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.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     Type      |   Length=1    |             PAN ID            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|      Padding (all zeros)      |          Short Address        |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
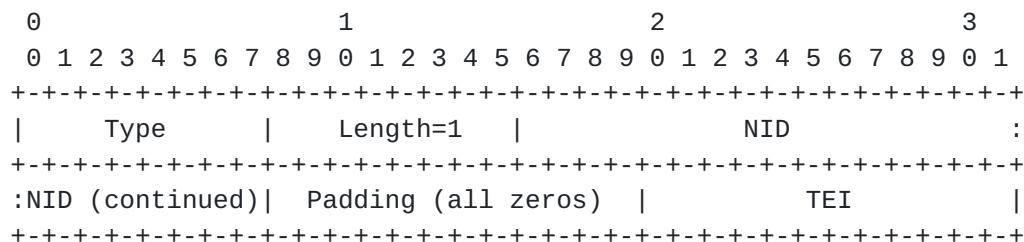
          Figure 4: Unicast Address Mapping for IEEE 1901.2

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.

For IPv6 address prefix dissemination, Router Solicitations (RS) and
Router Advertisements (RA) MAY be used as per [RFC6775]. 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. In this case, the prefix information option
(PIO) MUST NOT be included in the Router Advertisement.

For context information dissemination, Router Advertisements (RA)
MUST be used as per [RFC6775]. The 6LoWPAN context option (6CO) MUST
be included in the RA to disseminate the Context IDs used for prefix
compression.

For address registration, a PLC host MUST register its address to the
router using Neighbor Solicitation and Neighbor Advertisement
messages. RFC6775-update PLC devices MUST include the EARO with the
'R' flag set when sending Neighbor Solicitations, and process
Neighbor Advertisements that include EARO to extract status
information. 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. Otherwise,
DAD MUST be performed: RFC6775-only PLC devices MUST perform multihop
DAD against a 6LBR by using DAR and DAC messages, while for
RFC6775-update devices, DAD is proxied by a routing registrar, which
MAY operate according to Optimistic DAD (ODAD) [RFC4429].

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.

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
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. Fragmentation and reassembly is still required at the
adaptation layer, if the MAC layer cannot support the minimum MTU
demanded by IPv6, which is 1280 octets.

In IEEE 1901.1 and IEEE 1901.2, since the MAC layer supports payloads
of 2031 octets and 1576 octets respectively, fragmentation is not
needed for IPv6 packet transmission. The fragmentation and
reassembly defined in [RFC4944] SHOULD 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.

```
    0                   1                   2                   3
    0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |     ESC       |  Command ID   |     Command Payload
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
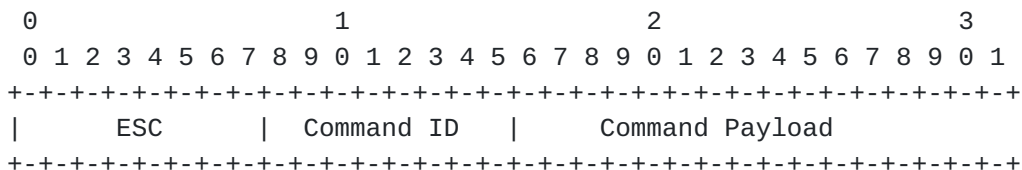
          Figure 5: Command Frame Header Format of ITU-T G.9903

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 (PANC) and PAN Device. The PANC is the primary
coordinator of the PLC subnet and can be seen as a master node; PAN
Devices are typically PLC meters and sensors. The PANC 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 PANC 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 single-hop
star topologies, communication at the link layer only takes place
between a PAN Device and a PANC. The PANC typically collects data
(e.g. a 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.

```
                PAN Device    PAN Device
                     \         /           +---------
                      \       /           /
                       \     /           +
                        \   /            |
         PAN Device ------ PANC ==========+  Internet
                        /  \             |
                       /    \            +
                      /      \            \
                     /        \           +---------
                PAN Device    PAN Device


            <---------------------->
            PLC subnet (IPv6 over PLC)
```
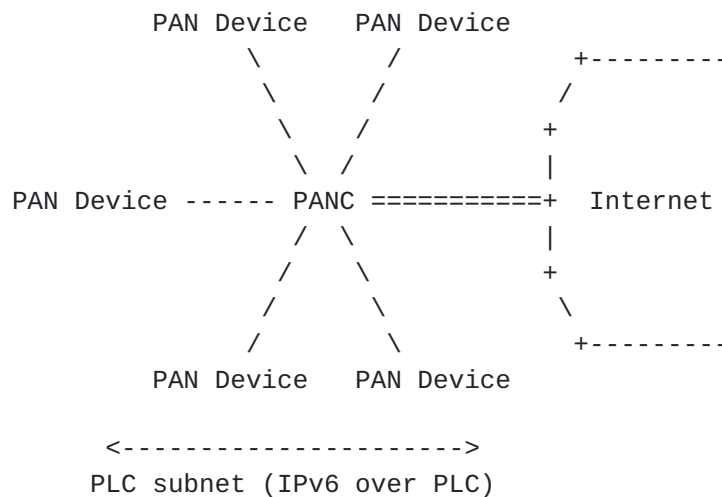
               Figure 7: PLC Star Network connected to the Internet

   A tree topology is useful when the distance between a device A and
   PANC is beyond the PLC allowed limit and there is another device B in
   between able to communicate with both sides. Device B in this case
   acts both as a PAN Device and a Coordinator. For this scenario, the
   link layer communications take place between device A and device B,
   and between device B and PANC. 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
   provide information such as light intensity, 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 is depicted in [RFC8036]. A tree
   topology is suitable for AMI scenarios that require large coverage
   but low density, e.g. the deployment of smart meters in rural areas.
   RPL is suitable for maintenance of a tree topology in which there is
   no need for communication directly between PAN devices.

```
                      PAN Device
                        \                      +---------
           PAN Device    \                    /
              \           \                   +
               \           \                  |
             PAN Device -- PANC ===========+  Internet
               /          /                  |
              /          /                    +
   PAN Device---PAN Device    /                \
                        /                      +---------
         PAN Device---PAN Device

         <------------------------->
         PLC subnet (IPv6 over PLC)
```
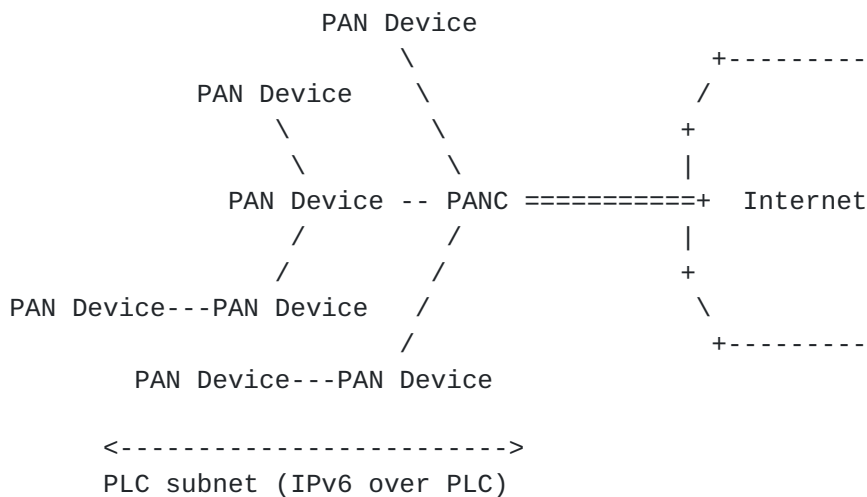
          Figure 8: PLC Tree Network connected to the Internet

   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 device communication, without being
   obliged to transmit frames through the PANC, which is a requirement
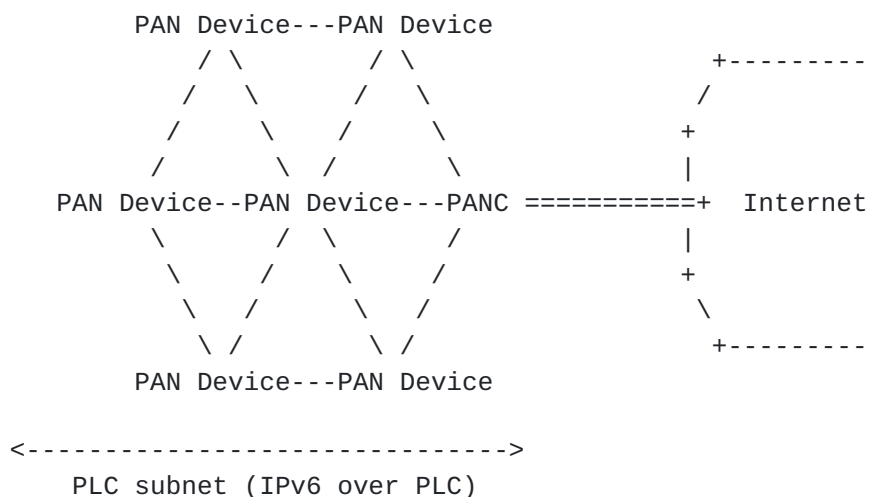   often cited for AMI infrastructure.

```
          PAN Device---PAN Device
            / \        / \                      +---------
           /   \      /   \                    /
          /     \    /     \                  +
         /       \  /       \                 |
      PAN Device--PAN Device---PANC ==========+  Internet
         \        / \        /                |
          \      /   \      /                 +
           \    /     \    /                   \
            \  /       \  /                    +---------
         PAN Device---PAN Device

      <------------------------------->
          PLC subnet (IPv6 over PLC)
```

          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.

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9. References

9.1. Normative References

[I-D.ietf-6lo-rfc6775-update]
          Thubert, P., Nordmark, E., Chakrabarti, S., and C.
          Perkins, "Registration Extensions for 6LoWPAN Neighbor
          Discovery", draft-ietf-6lo-rfc6775-update-21 (work in
          progress), June 2018.

[I-D.ietf-roll-aodv-rpl]
          Anamalamudi, S., Zhang, M., Perkins, C., Anand, S., and B.
          Liu, "Asymmetric AODV-P2P-RPL in Low-Power and Lossy
          Networks (LLNs)", draft-ietf-roll-aodv-rpl-05 (work in
          progress), October 2018.

   [IEEE_1901.1]
            IEEE-SA Standards Board, "Standard for Medium Frequency
            (less than 15 MHz) Power Line Communications for Smart
            Grid Applications", IEEE 1901.1, May 2018,
            <http://sites.ieee.org/sagroups-1901-1>.

   [IEEE_1901.2]
            IEEE-SA Standards Board, "IEEE Standard for Low-Frequency
            (less than 500 kHz) Narrowband Power Line Communications
            for Smart Grid Applications", IEEE 1901.2, October 2013,
            <https://standards.ieee.org/findstds/
            standard/1901.2-2013.html>.

   [ITU-T_G.9903]
            International Telecommunication Union, "Narrowband
            orthogonal frequency division multiplexing power line
            communication transceivers for G3-PLC networks",
            ITU-T G.9903, February 2014,
            <https://www.itu.int/rec/T-REC-G.9903>.

   [RFC2119] Bradner, S., "Key words for use in RFCs to Indicate
            Requirement Levels", BCP 14, RFC 2119,
            DOI 10.17487/RFC2119, March 1997,
            <https://www.rfc-editor.org/info/rfc2119>.

   [RFC2464] Crawford, M., "Transmission of IPv6 Packets over Ethernet
            Networks", RFC 2464, DOI 10.17487/RFC2464, December 1998,
            <https://www.rfc-editor.org/info/rfc2464>.

   [RFC4861] Narten, T., Nordmark, E., Simpson, W., and H. Soliman,
            "Neighbor Discovery for IP version 6 (IPv6)", RFC 4861,
            DOI 10.17487/RFC4861, September 2007,
            <https://www.rfc-editor.org/info/rfc4861>.

   [RFC4944] Montenegro, G., Kushalnagar, N., Hui, J., and D. Culler,
            "Transmission of IPv6 Packets over IEEE 802.15.4
            Networks", RFC 4944, DOI 10.17487/RFC4944, September 2007,
            <https://www.rfc-editor.org/info/rfc4944>.

   [RFC6282] Hui, J., Ed. and P. Thubert, "Compression Format for IPv6
            Datagrams over IEEE 802.15.4-Based Networks", RFC 6282,
            DOI 10.17487/RFC6282, September 2011,
            <https://www.rfc-editor.org/info/rfc6282>.

   [RFC6550] Winter, T., Ed., Thubert, P., Ed., Brandt, A., Hui, J.,
              Kelsey, R., Levis, P., Pister, K., Struik, R., Vasseur,
              JP., and R. Alexander, "RPL: IPv6 Routing Protocol for
              Low-Power and Lossy Networks", RFC 6550,
              DOI 10.17487/RFC6550, March 2012,
              <https://www.rfc-editor.org/info/rfc6550>.

   [RFC6775] Shelby, Z., Ed., Chakrabarti, S., Nordmark, E., and C.
              Bormann, "Neighbor Discovery Optimization for IPv6 over
              Low-Power Wireless Personal Area Networks (6LoWPANs)",
              RFC 6775, DOI 10.17487/RFC6775, November 2012,
              <https://www.rfc-editor.org/info/rfc6775>.

9.2. Informative References

   [I-D.popa-6lo-6loplc-ipv6-over-ieee19012-networks]
              Popa, D. and J. Hui, "6LoPLC: Transmission of IPv6 Packets
              over IEEE 1901.2 Narrowband Powerline Communication
              Networks", draft-popa-6lo-6loplc-ipv6-over-
              ieee19012-networks-00 (work in progress), March 2014.

   [IEEE_1901.2a]
              IEEE-SA Standards Board, "IEEE Standard for Low-Frequency
              (less than 500 kHz) Narrowband Power Line Communications
              for Smart Grid Applications - Amendment 1", IEEE 1901.2a,
              September 2015, <https://standards.ieee.org/findstds/
              standard/1901.2a-2015.html>.

   [RFC3315] Droms, R., Ed., Bound, J., Volz, B., Lemon, T., Perkins,
              C., and M. Carney, "Dynamic Host Configuration Protocol
              for IPv6 (DHCPv6)", RFC 3315, DOI 10.17487/RFC3315, July
              2003, <https://www.rfc-editor.org/info/rfc3315>.

   [RFC3972] Aura, T., "Cryptographically Generated Addresses (CGA)",
              RFC 3972, DOI 10.17487/RFC3972, March 2005,
              <https://www.rfc-editor.org/info/rfc3972>.

   [RFC4291] Hinden, R. and S. Deering, "IP Version 6 Addressing
              Architecture", RFC 4291, DOI 10.17487/RFC4291, February
              2006, <https://www.rfc-editor.org/info/rfc4291>.

   [RFC4429] Moore, N., "Optimistic Duplicate Address Detection (DAD)
              for IPv6", RFC 4429, DOI 10.17487/RFC4429, April 2006,
              <https://www.rfc-editor.org/info/rfc4429>.

   [RFC4941] Narten, T., Draves, R., and S. Krishnan, "Privacy
              Extensions for Stateless Address Autoconfiguration in
              IPv6", RFC 4941, DOI 10.17487/RFC4941, September 2007,
              <https://www.rfc-editor.org/info/rfc4941>.

   [RFC5535] Bagnulo, M., "Hash-Based Addresses (HBA)", RFC 5535,
              DOI 10.17487/RFC5535, June 2009,
              <https://www.rfc-editor.org/info/rfc5535>.

   [RFC7217] Gont, F., "A Method for Generating Semantically Opaque
              Interface Identifiers with IPv6 Stateless Address
              Autoconfiguration (SLAAC)", RFC 7217,
              DOI 10.17487/RFC7217, April 2014,
              <https://www.rfc-editor.org/info/rfc7217>.

   [RFC8036] Cam-Winget, N., Ed., Hui, J., and D. Popa, "Applicability
              Statement for the Routing Protocol for Low-Power and Lossy
              Networks (RPL) in Advanced Metering Infrastructure (AMI)
              Networks", RFC 8036, DOI 10.17487/RFC8036, January 2017,
              <https://www.rfc-editor.org/info/rfc8036>.

   [RFC8065] Thaler, D., "Privacy Considerations for IPv6 Adaptation-
              Layer Mechanisms", RFC 8065, DOI 10.17487/RFC8065,
              February 2017, <https://www.rfc-editor.org/info/rfc8065>.

   [RFC8066] Chakrabarti, S., Montenegro, G., Droms, R., and J.
              Woodyatt, "IPv6 over Low-Power Wireless Personal Area
              Network (6LoWPAN) ESC Dispatch Code Points and
              Guidelines", RFC 8066, DOI 10.17487/RFC8066, February
              2017, <https://www.rfc-editor.org/info/rfc8066>.

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