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IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) Dispatch Type for SCHC

draft-gomez-6lo-schc-dispatch-01

Abstract

A new framework called Static Context Header Compression (SCHC) has been designed with the primary goal of supporting IPv6 over Low Power Wide Area Network (LPWAN) technologies [RFC8724]. One of the SCHC components is a header compression mechanism. If used properly, SCHC header compression allows a greater compression ratio than that achievable with traditional 6LoWPAN header compression [RFC6282]. For this reason, it may make sense to use SCHC header compression in some 6LoWPAN environments. This document defines a 6LoWPAN Dispatch Type to signal when a packet header has been compressed by using SCHC header compression.

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1. Introduction

RFC 6282 is the main specification for IPv6 over Low power Wireless Personal Area Network (6LoWPAN) IPv6 header compression [RFC6282]. This RFC was designed assuming IEEE 802.15.4 as the layer below the 6LoWPAN adaptation layer, and it has also been reused (with proper adaptations) for IPv6 header compression over many other technologies relatively similar to IEEE 802.15.4 in terms of characteristics such as physical layer bit rate, layer 2 maximum payload size, etc. Examples of such technologies comprise BLE, DECT-ULE, ITU G.9959, MS/TP, NFC, and PLC. RFC 6282 provides additional functionality, such as a mechanism for UDP header compression.

In the best cases, RFC 6282 allows to compress a 40-byte IPv6 header down to a 2-byte compressed header (for link-local interactions) or a 3-byte compressed header (when global IPv6 addresses are used). On the other hand, an RFC 6282 compressed UDP header has a typical size of 4 bytes. Therefore, in advantageous conditions, a 48-byte uncompressed IPv6/UDP header may be compressed down to a 6-byte format (when using link-local addresses) or a 7-byte format (for global interactions) by using RFC 6282.

Recently, a new framework called Static Context Header Compression (SCHC) has been designed with the primary goal of supporting IPv6 over Low Power Wide Area Network (LPWAN) technologies [RFC8724]. SCHC comprises header compression and fragmentation functionality tailored to the extraordinary constraints of LPWAN technologies, which are more severe than those exhibited by IEEE 802.15.4 or other relatively similar technologies.

SCHC header compression allows a greater compression ratio than that of RFC 6282. If used properly, SCHC allows to compress an IPv6/UDP header down to e.g. a single byte. Therefore, it may make sense to use SCHC header compression in some 6LoWPAN environments [I-D.toutain-6lo-6lo-and-schc], considering its greater efficiency.

If SCHC header compression is added to the panoply of header compression mechanisms used in 6LoWPAN environments, then there is a need to signal when a packet header has been compressed by using SCHC. To this end, in its current form, the present document specifies a 6LoWPAN Dispatch Type for SCHC header compression, based on exploiting RFC 8025 Dispatch type space [RFC8025].

2. Conventions used in this document

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL","SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC2119].

3. Frame Format

Figure 1 illustrates the content of an encapsulated, SCHC compressed, IPv6 datagram:

```
+---------------+-------------+---------+
| SCHC Dispatch | SCHC Header | Payload |
+---------------+-------------+---------+
```

Figure 1: Encapsulated, SCHC compressed IPv6 datagram

The SCHC Dispatch is a 6LoWPAN Dispatch Type that indicates that the next field is a SCHC Header. The latter corresponds to a packet header that has been compressed by using SCHC. As defined in [RFC8724], the SCHC Header comprises a Rule ID, and a compression residue. (Note: more details, including a discussion on padding, to be added.)

4. SCHC Dispatch Type

This section defines the 6LoWPAN Dispatch Type called "SCHC Dispatch", by using the RFC 8025 concept of "pages". With the aim to minimize overhead, the present document allocates a whole page (Page 2) for the SCHC Dispatch Type:

SCHC Dispatch Type bit pattern: 11110010 (Page 2 (Note: to be confirmed by IANA))

For example, two bytes may be used for the SCHC Dispatch plus the Rule ID, which offers a Rule ID space of 256 possible Rule IDs.

5. IANA Considerations

This document requests the allocation of the Dispatch Type Field bit pattern 11110010 (Page 2) as SCHC Dispatch Type.

6. Security Considerations

TBD

7. Acknowledgments

Ana Minaburo and Laurent Toutain suggested for the first time the use of SCHC in environments where 6LoWPAN has traditionally been used. Laurent Toutain made comments that helped shape this document.

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8.1. Normative References

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8.2. Informative References

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IPv6 Mesh over BLUETOOTH(R) Low Energy using IPSP
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Abstract

RFC 7668 describes the adaptation of 6LoWPAN techniques to enable IPv6 over Bluetooth low energy networks that follow the star topology. However, recent Bluetooth specifications allow the formation of extended topologies as well. This document specifies mechanisms that are needed to enable IPv6 mesh over Bluetooth Low Energy links established by using the Bluetooth Internet Protocol Support Profile. This document does not specify the routing protocol to be used in an IPv6 mesh over Bluetooth LE links.

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1. Introduction

Bluetooth Low Energy (hereinafter, Bluetooth LE) was first introduced in the Bluetooth 4.0 specification. Bluetooth LE (which has been marketed as Bluetooth Smart) is a low-power wireless technology designed for short-range control and monitoring applications. Bluetooth LE is currently implemented in a wide range of consumer electronics devices, such as smartphones and wearable devices. Given the high potential of this technology for the Internet of Things, the Bluetooth Special Interest Group (Bluetooth SIG) and the IETF have produced specifications in order to enable IPv6 over Bluetooth LE, such as the Internet Protocol Support Profile (IPSP) [IPSP], and RFC 7668 [RFC7668], respectively. Bluetooth 4.0 only supports Bluetooth LE networks that follow the star topology. As a consequence, RFC 7668 [RFC7668] was specifically developed and optimized for that type of network topology. However, the functionality described in RFC

7668 [RFC7668] is not sufficient and would fail to enable an IPv6 mesh over Bluetooth LE links. This document specifies mechanisms that are needed to enable IPv6 mesh over Bluetooth LE links. This document does not specify the routing protocol to be used in an IPv6 mesh over Bluetooth LE links.

1.1. Terminology and Requirements Language

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP14 RFC 2119 [RFC2119], RFC 8174 [RFC8174], when, and only when, they appear in all capitals, as shown here.

The terms 6LoWPAN Node (6LN), 6LoWPAN Router (6LR) and 6LoWPAN Border Router (6LBR) are defined as in [RFC6775], with an addition that Bluetooth LE central and Bluetooth LE peripheral (see Section 2) can both be adopted by a 6LN, a 6LR or a 6LBR.

2. Bluetooth LE Networks and the IPSP

Bluetooth LE defines two Generic Access Profile (GAP) roles of relevance herein: the Bluetooth LE central role and the Bluetooth LE peripheral role. A device in the central role, which is called central from now on, has traditionally been able to manage multiple simultaneous connections with a number of devices in the peripheral role, called peripherals hereinafter. Bluetooth 4.1 (now deprecated) introduced the possibility for a peripheral to be connected to more than one central simultaneously, therefore allowing extended topologies beyond the star topology for a Bluetooth LE network. In addition, a device may simultaneously be a central in a set of link layer connections, as well as a peripheral in others.

On the other hand, the IPSP enables discovery of IP-enabled devices and the establishment of a link layer connection for transporting IPv6 packets. The IPSP defines the Node and Router roles for devices that consume/originate IPv6 packets and for devices that can route IPv6 packets, respectively. Consistently with Bluetooth 4.1 and subsequent Bluetooth versions (e.g. Bluetooth 4.2 [BTCorev4.2] or subsequent), a device may implement both roles simultaneously.

This document assumes a mesh network composed of Bluetooth LE links, where link layer connections are established between neighboring IPv6-enabled devices (see Section 3.3.2, item 3.b, and an example in Appendix A)). The IPv6 forwarding devices of the mesh have to implement both IPSP Node and Router roles, while simpler leaf-only nodes can implement only the Node role. In an IPv6 mesh over Bluetooth LE links, a node is a neighbor of another node, and vice versa, if a link layer connection has been established between both by using the IPSP functionality for discovery and link layer connection establishment for IPv6 packet transport.

3. Specification of IPv6 mesh over Bluetooth LE links

3.1. Protocol stack

Figure 1 illustrates the protocol stack for IPv6 mesh over Bluetooth LE links. The core Bluetooth LE protocol stack comprises two main sections: the Controller, and the Host. The former includes the Physical Layer, and the Link Layer, whereas the latter is composed of the Logical Link Control and Adaptation Protocol (L2CAP), the Attribute Protocol (ATT), and the Generic Attribute Profile (GATT). The Host and the Controller sections are connected by means of the Host-Controller Interface (HCI). A device that supports the IPSP Node role instantiates one Internet Protocol Support Service (IPSS), which runs atop GATT. The protocol stack shown in Figure 1 shows two main differences with the IPv6 over Bluetooth LE stack in RFC 7668: a) the adaptation layer below IPv6 (labelled as "6Lo for IPv6 mesh over Bluetooth LE") is now adapted for IPv6 mesh over Bluetooth LE links, and b) the protocol stack for IPv6 mesh over Bluetooth LE links includes IPv6 routing functionality.

```
                           +------------------------------------+
                           |            Application             |
             +---------+   +------------------------------------+
             |  IPSS   |   |            UDP/TCP/other           |
             +---------+   +------------------------------------+
             |  GATT   |   |            IPv6  |routing|         |
             +---------+   +------------------------------------+
             |  ATT    |   | 6Lo for IPv6 mesh over Bluetooh LE |
             +---------+--+------------------------------------+
             |               Bluetooth LE L2CAP                 |
        HCI - - +--------------------------------------------------+ - -
             |             Bluetooth LE Link Layer              |
             +--------------------------------------------------+
             |           Bluetooth LE Physical Layer            |
             +--------------------------------------------------+
```

Figure 1: Protocol stack for IPv6 mesh over Bluetooth LE links.

Bluetooth 4.2 defines a default MTU for Bluetooth LE of 251 bytes. Excluding the L2CAP header of 4 bytes, a protocol data unit (PDU) size of 247 bytes is available for the layer above L2CAP. (Note: earlier Bluetooth LE versions offered a maximum amount of 23 bytes for the layer atop L2CAP.) The L2CAP provides a fragmentation and reassembly solution for transmitting or receiving larger PDUs. At each link, the IPSP defines means for negotiating a link-layer connection that provides an MTU of 1280 octets or higher for the IPv6 layer [IPSP]. For the sake of lightweight implementation and operation, an MTU of 1280 octets is RECOMMENDED for IPv6 mesh over BLE links. The link-layer MTU is negotiated separately for each direction. Implementations that require an equal link-layer MTU for the two directions SHALL use the smallest of the possibly different MTU values.

Note that this specification allows using different MTUs in different links. If an implementation requires use of the same MTU on every one of its links, and a new node with a smaller MTU is added to the network, a renegotiation of one or more links can occur. In the worst case, the renegotiations could cascade network-wide. In that case, implementers need to assess the impact of such phenomenon.

Similarly to RFC 7668, fragmentation functionality from 6LoWPAN standards is not used for IPv6 mesh over Bluetooth LE links. Bluetooth LE’s fragmentation support provided by L2CAP is used when necessary.

3.2. Subnet model

For IPv6 mesh over Bluetooth LE links, a multilink model has been chosen, as further illustrated in Figure 2. As IPv6 over Bluetooth LE is intended for constrained nodes, and for Internet of Things use cases and environments, the complexity of implementing a separate subnet on each peripheral-central link and routing between the subnets appears to be excessive. In this specification, the benefits of treating the collection of point-to-point links between a central and its connected peripherals as a single multilink subnet rather than a multiplicity of separate subnets are considered to outweigh the multilink model’s drawbacks as described in [RFC4903]. Note that the route-over functionality defined in [RFC6775] is essential to enable the multilink subnet model for IPv6 mesh over Bluetooth LE links.

```
                                                          /
       .--------------------------------.                /
      /     6LR           6LN       6LN \               /
     /         \             \         \ \             /
    |           \             \         \ |           /
    |  6LN ----- 6LR --------- 6LR ------ 6LBR ----- |  Internet
    |   <--Link--> <---Link--->/<--Link->/ |         |
     \                        /         / /           \
      \           6LN ---- 6LR ----- 6LR /             \
       '--------------------------------'               \
                                                         \

     <------------ Subnet ----------------->&lt;---- IPv6 connection -->
                                                  to the Internet
```

Figure 2: Example of an IPv6 mesh over a Bluetooth LE network connected to the Internet

One or more 6LBRs are connected to the Internet. 6LNs are connected to the network through a 6LR or a 6LBR. A single Global Unicast prefix is used on the whole subnet.

IPv6 mesh over Bluetooth LE links MUST follow a route-over approach. This document does not specify the routing protocol to be used in an IPv6 mesh over Bluetooth LE links.

3.3. Link model

3.3.1. Stateless address autoconfiguration

6LN, 6LR, and 6LBR IPv6 addresses in an IPv6 mesh over Bluetooth LE links are configured as per section 3.2.2 of RFC 7668.

Multihop Duplicate Address Detection (DAD) functionality as defined in section 8.2 of RFC 6775 and updated by RFC 8505, or some substitute mechanism (see section 3.3.2), MAY be supported.

3.3.2. Neighbor Discovery

'Neighbor Discovery Optimization for IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs)' [RFC6775], subsequently updated by 'Registration Extensions for IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) Neighbor Discovery' [RFC8505], describes the neighbor discovery functionality adapted for use in several 6LoWPAN topologies, including the mesh topology. The route-over functionality of RFC 6775 and RFC 8505 MUST be supported.

The following aspects of the Neighbor Discovery optimizations for 6LoWPAN [RFC6775],[RFC8505] are applicable to Bluetooth LE 6LNs:

1. A Bluetooth LE 6LN SHOULD register its non-link-local addresses with its routers by sending a Neighbor Solicitation (NS) message with the Extended Address Registration Option (EARO) and process the Neighbor Advertisement (NA) accordingly. Note that in some cases (e.g., very short-lived connections) it may not be worthwhile for a 6LN to send an NS with EARO for registering its address. However, the consequences of not registering the address (including non-reachability of the 6LN, and absence of DAD) need to be carefully considered. The EARO option includes a Registration Ownership Verifier (ROVR) field [RFC8505]. In the case of Bluetooth LE, by default the ROVR field is filled with the 48-bit device address used by the Bluetooth LE node converted into 64-bit Modified EUI-64 format [RFC4291]. Optionally, a cryptographic ID (see RFC 8928 [RFC8928]) MAY be placed in the ROVR field. If a cryptographic ID is used, address registration and multihop DAD formats and procedures defined in RFC 8928 MUST be used, unless an alternative mechanism offering equivalent protection is used. As per RFC 8505, a 6LN MUST NOT register its link-local address.

If the 6LN registers multiple addresses that are not based on the Bluetooth device address using the same compression context, the header compression efficiency may decrease, since only the last registered address can be fully elided (see Section 3.2.4 of RFC 7668).

2. For sending Router Solicitations and processing Router Advertisements, the hosts that participate in an IPv6 mesh over BLE MUST, respectively, follow Sections 5.3 and 5.4 of [RFC6775], and Section 5.6 of [RFC8505].

3. The router behavior for 6LRs and 6LBRs is described in Section 6 of RFC 6775, and updated by RFC 8505. However, as per this specification: a) Routers SHALL NOT use multicast NSs to discover other routers' link layer addresses. b) As per section 6.2 of RFC 6775, in a dynamic configuration scenario, a 6LR comes up as a non-router and waits to receive a Router Advertisement for configuring its own interface address first, before setting its interfaces to be advertising interfaces and turning into a router. In order to support such operation in an IPv6 mesh over Bluetooth LE links, a 6LR first uses the IPSP Node role only. Once the 6LR has established a connection with another node currently running as a router, and receives a Router Advertisement from that router, the 6LR configures its own interface address, it turns into a router, and it runs as an IPSP Router. In contrast with a 6LR, a 6LBR uses the IPSP Router role since the 6LBR is initialized, that is, the 6LBR uses both the

IPSP Node and IPSP Router roles at all times. See an example in Appendix B..

4. Border router behavior is described in Section 7 of RFC 6775, and updated by RFC 8505.

RFC 6775 defines substitutable mechanisms for distributing prefixes and context information (section 8.1 of RFC 6775), as well as for Duplicate Address Detection across a route-over 6LoWPAN (section 8.2 of RFC 6775). RFC 8505 updates those mechanisms and the related message formats. Implementations of this specification MUST either support the features described in sections 8.1 and 8.2 of RFC 6775, as updated by RFC 8505, or some alternative ("substitute") mechanism.

3.3.3. Header compression

Header compression as defined in RFC 6282 [RFC6282], which specifies the compression format for IPv6 datagrams on top of IEEE 802.15.4, is REQUIRED as the basis for IPv6 header compression on top of Bluetooth LE. All headers MUST be compressed according to RFC 6282 [RFC6282] encoding formats.

To enable efficient header compression, when the 6LBR sends a Router Advertisement it MAY include a 6LoWPAN Context Option (6CO) [RFC6775] matching each address prefix advertised via a Prefix Information Option (PIO) [RFC4861] for use in stateless address autoconfiguration. Note that 6CO is not needed for context-based compression when context is pre-provisioned or provided by out-of-band means.

The specific optimizations of RFC 7668 for header compression, which exploited the star topology and ARO (note that the latter has been updated by EARO as per RFC 8505), cannot be generalized in an IPv6 mesh over Bluetooth LE links. Still, a subset of those optimizations can be applied in some cases in such a network. These cases comprise link-local interactions, non-link-local packet transmissions originated by a 6LN (i.e. the first hop from a 6LN), and non-link-local packets intended for a 6LN that are originated or forwarded by a neighbor of that 6LN (i.e. the last hop toward a 6LN). For all other packet transmissions, context-based compression MAY be used.

When a device transmits a packet to a neighbor, the sender MUST fully elide the source IID if the source IPv6 address is the link-local address based on the sender's Bluetooth device address (SAC=0, SAM=11). The sender also MUST fully elide the destination IPv6 address if it is the link-local address based on the neighbor's Bluetooth device address (DAC=0, DAM=11).

When a 6LN transmits a packet, with a non-link-local source address that the 6LN has registered with EARO in the next-hop router for the indicated prefix, the source address MUST be fully elided if it is the latest address that the 6LN has registered for the indicated prefix (SAC=1, SAM=11). If the source non-link-local address is not the latest registered by the 6LN, and the first 48 bits of the IID match with the latest address registered by the 6LN, then the last 16 bits of the IID SHALL be carried in-line (SAC=1, SAM=10). Otherwise, if the first 48 bits of the IID do not match, then the 64 bits of the IID SHALL be fully carried in-line (SAC=1, SAM=01).

When a router transmits a packet to a neighboring 6LN, with a non-link-local destination address, the router MUST fully elide the destination IPv6 address if the destination address is the latest registered by the 6LN with EARO for the indicated context (DAC=1, DAM=11). If the destination address is a non-link-local address and not the latest registered, and the first 48 bits of the IID match to those of the latest registered address, then the last 16 bits of the IID SHALL be carried in-line (DAC=1, DAM=10). Otherwise, if the first 48 bits of the IID do not match, then the 64 bits of the IID SHALL be fully carried in-line (DAC=1, DAM=01).

3.3.4. Unicast and multicast mapping

The Bluetooth LE Link Layer does not support multicast. Hence, traffic is always unicast between two Bluetooth LE neighboring nodes. If a node needs to send a multicast packet to several neighbors, it has to replicate the packet and unicast it on each link. However, this may not be energy efficient, and particular care must be taken if the node is battery powered. A router (i.e., a 6LR or a 6LBR) MUST keep track of neighboring multicast listeners, and it MUST NOT forward multicast packets to neighbors that have not registered as listeners for multicast groups to which the packets are destined.

4. IANA Considerations

There are no IANA considerations related to this document.

5. Security Considerations

The security considerations in RFC 7668 apply.

IPv6 mesh over Bluetooth LE links requires a routing protocol to find end-to-end paths. Unfortunately, the routing protocol may generate additional opportunities for threats and attacks to the network.

RFC 7416 [RFC7416] provides a systematic overview of threats and attacks on the IPv6 Routing Protocol for Low-Power and Lossy Networks

(RPL), as well as countermeasures. In that document, described threats and attacks comprise threats due to failures to authenticate, threats due to failure to keep routing information, threats and attacks on integrity, and threats and attacks on availability. Reported countermeasures comprise confidentiality attack, integrity attack, and availability attack countermeasures.

While this specification does not state the routing protocol to be used in IPv6 mesh over Bluetooth LE links, the guidance of RFC 7416 is useful when RPL is used in such scenarios. Furthermore, such guidance may partly apply for other routing protocols as well.

The ROVR can be derived from the Bluetooth device address. However, such a ROVR can be spoofed, and therefore, any node connected to the subnet and aware of a registered-address-to-ROVR mapping could perform address theft and impersonation attacks. Use of Address Protected Neighbor Discovery RFC 8928 [RFC8928] provides protection against such attacks.

6. Contributors

Carlo Alberto Boano (Graz University of Technology) contributed to the design and validation of this document.

7. Acknowledgements

The Bluetooth, Bluetooth Smart and Bluetooth Smart Ready marks are registered trademarks owned by Bluetooth SIG, Inc.

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8. Appendix A: Bluetooth LE connection establishment example

This appendix provides an example of Bluetooth LE connection establishment and use of IPSP roles in an IPv6 mesh over Bluetooth LE links that uses dynamic configuration. The example follows text in Section 3.3.2, item 3.b).

The example assumes a network with one 6LBR, two 6LRs and three 6LNs, as shown in Figure 3. Connectivity between the 6LNs and the 6LBR is only possible via the 6LRs.

The following text describes the different steps as time evolves, in the example. Note that other sequences of events that may lead to the same final scenario are also possible.

At the beginning, the 6LBR starts running as an IPSP Router, whereas the rest of devices are not yet initialized (Step 1). Next, the 6LRs start running as IPSP Nodes, i.e., they use Bluetooth LE advertisement packets to announce their presence and support of IPv6 capabilities (Step 2). The 6LBR (already running as an IPSP Router) discovers the presence of the 6LRs and establishes one Bluetooth LE connection with each 6LR (Step 3). After establishment of those link layer connections (and after reception of Router Advertisements from the 6LBR), Step 4, the 6LRs start operating as routers, and also initiate the IPSP Router role (note: whether the IPSP Node role is kept running simultaneously is an implementation decision). Then, 6LNs start running the IPSP Node role (Step 5). Finally, the 6LRs discover presence of the 6LNs and establish connections with the latter (Step 6).

```
Step 1
******
                                     6LBR
                                (IPSP: Router)


                          6LR                   6LR
                   (not initialized)     (not initialized)



            6LN                 6LN                    6LN
    (not initialized)    (not initialized)     (not initialized)
```

```
Step 2
******
```

```
                                        6LBR
                                   (IPSP: Router)


                              6LR                 6LR
                         (IPSP: Node)        (IPSP: Node)



                6LN                 6LN                  6LN
         (not initialized)     (not initialized)    (not initialized)
```

```
   Step 3
   ******

                                        6LBR
                                   (IPSP: Router)
     Bluetooth LE connection -->   /            \
                                  /              \
                              6LR                 6LR
                         (IPSP: Node)        (IPSP: Node)



                6LN                 6LN                  6LN
         (not initialized)     (not initialized)    (not initialized)
```

```
   Step 4
   ******

                                        6LBR
                                   (IPSP: Router)
                                   /            \
                                  /              \
                              6LR                 6LR
                         (IPSP: Router)     (IPSP: Router)
```

```
                6LN                 6LN                  6LN
       (not initialized)      (not initialized)     (not initialized)


   Step 5
   ******

                                        6LBR
                                   (IPSP: Router)
                                   /            \
                                  /              \
                              6LR                 6LR
                         (IPSP: Router)      (IPSP: Router)



                6LN                   6LN                6LN
            (IPSP: Node)         (IPSP: Node)        (IPSP: Node)


   Step 6
   ******

                                        6LBR
                                   (IPSP: Router)
                                   /            \
                                  /              \
                              6LR                 6LR
                        (IPSP: Router)       (IPSP: Router)
                         /           \       /            \
                        /             \     /              \
                       /               \   /                \
                    6LN                 6LN                  6LN
               (IPSP: Node)         (IPSP: Node)         (IPSP: Node)
```

Figure 3: An example of connection establishment and use of IPSP roles in an IPv6 mesh over Bluetooth LE links.

9. Appendix B: Node joining procedure

This appendix provides a diagram that illustrates the node joining procedure. First of all, the joining node advertises its presence in order to allow establishing Bluetooth LE connections with neighbors that already belong to a network. The latter typically run as a 6LR or as a 6LBR. After Bluetooth LE connection establishment, the joining node starts acting as a 6LN.

Figure 4 shows the sequence of messages that are exchanged by the 6LN and a neighboring 6LR that already belongs to the network, after the establishment of a Bluetooth LE connection between both devices. Initially, the 6LN sends an RS message (1). Then, the 6LR replies with an RA, which includes the PIO (2). After discovering the non-link-local prefix in use in the network, the 6LN creates its non-link-local address, registers that address with EARO (3) in the 6LR, and multihop DAD is performed (4). The next step is the transmission of the NA message sent by the 6LR in response to the NS previously sent by the 6LN (5). If the non-link-local address of the 6LN has been successfully validated, the 6LN can operate as a member of the network it has joined.

```
           (1)                 6LN ----(RS)-------> 6LR
           (2)                 6LN <---(RA-PIO)---- 6LR
           (3)                 6LN ----(NS-EARO)--> 6LR
           (4)                 [Multihop DAD procedure]
           (5)                 6LN <---(NA)-------- 6LR
```

Figure 4: Message exchange diagram for a joining node

10. References

10.1. Normative References

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Transmission of IPv6 Packets over PLC Networks
draft-ietf-6lo-plc-05

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.

Table of Contents

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], [RFC6775] and [RFC8505] to constrained PLC networks. There was work previously proposed as [I-D.popa-6lo-6loplc-ipv6-over-ieee19012-networks], which did not reach consensus. This document provides a more structured specification than the previous work, expanding to a larger variety of 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 BCP14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

This document 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

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

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

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	This document
PAN Coordinator	Central Coordinator	PAN Coordinator	PAN Coordinator
Coordinator	Proxy Coordinator	Full-function device	Coordinator
Device	Station	PAN Device	PLC 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 of 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.

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, as explained in Section 3.4.

```
+-----------------------------------------+
|            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. Short addresses can be assigned during the onboarding process, by the PANC or the JRC (join registrar/coordinator) in CoJP (Constrained Join Protocol) [I-D.ietf-6tisch-minimal-security].

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 these two technologies can support IPv6 natively without fragmentation and reassembly, it is possible to configure a smaller MTU in high-noise communication environment. Thus the 6lo functions, including header compression, fragmentation and reassembly, are still applicable and useful.

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:

- 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.

- 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 (PANC in this document).

- 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 and 6lo standards [RFC4944], [RFC6282], [RFC6775], and [RFC8505] provides useful functionality including link-local IPv6 addresses, stateless address auto-configuration, neighbor discovery, header compression, fragmentation and reassembly. However, due to the different characteristics of the PLC media, the 6LoWPAN adaptation layer, as it is, cannot perfectly fulfill the requirements of PLC environments. 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 from the MAC address SHOULD only be used for link-local address configuration. A PLC host SHOULD use the IID derived from 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. Implementers should look at [RFC8064] as well, in order to generate a stable IPv6 address using an opaque IID.

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. [RFC8505] 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 [RFC8505]. 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, the IPv6 prefix MAY be disseminated by the layer 3 routing protocol, such as RPL, which may includes the prefix in the DIO message. As per [I-D.ietf-roll-unaware-leaves], it is possible to have PLC devices configured as RPL-unaware-leaves, which do not participate to RPL at all, along with RPL-aware PLC devices. In this case, the prefix dissemination SHOULD use the RS/RA messages.

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 and/or address compression.

For address registration in route-over mode, a PLC device MUST register its addresses by sending unicast link-local Neighbor Solicitation to the 6LR. If the registered address is link-local, the 6LR SHOULD NOT further register it to the registrar (6LBR, 6BBR). Otherwise, the address MUST be registered via an ARO or EARO included in the DAR ([RFC6775]) or EDAR ([RFC8505]) messages. For RFC8505 compliant PLC devices, the 'R' flag in the EARO MUST be set when sending Neighbor Solicitaitons in order to extract the status information in the replied Neighbor Advertisements from the 6LR. If DHCPv6 is used to assign addresses or the IPv6 address is derived from unique long or short link layer address, Duplicate Address Detection (DAD) MUST NOT be utilized. Otherwise, the DAD MUST be performed at the 6LBR (as per [RFC6775]) or proxied by the routing registrar (as per [RFC8505]). The registration status is feedbacked via the DAC or EDAC message from the 6LBR and the Neighbor Advertisement (NA) from the 6LR.

For address registration in mesh-under mode, since all the PLC devices are link-local neighbors to the 6LBR, DAR/DAC or EDAR/EDAC messages are not required. A PLC device MUST register its addresses by sending a unicast NS message with an ARO or EARO. The registration status is feedbacked via the NA message from the 6LBR.

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 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.

For IEEE 1901.2 and G.9903, the IP header compression follows the instruction in [RFC6282]. However, additional adaptation MUST be considered for IEEE 1901.1 since it has a short address of 12 bits instead of 16 bits. The only modification is the semantics of the "Source Address Mode" when set as "10" in the section 3.1 of [RFC6282], which is illustrated as following.

SAM: Source Address Mode:

If SAC=0: Stateless compression

10: 12 bits. The first 116 bits of the address are elided.The value of the first 64 bits is the link-local prefix padded with zeros. The following 64 bits are 0000:00ff:fe00:0XXX, where XXX are the 12 bits carried in-line.

If SAC=1: stateful context-based compression

10: 12 bits. The address is derived using context information and the 12 bits carried in-line. Bits covered by context information are always used. Any IID bits not covered by context information are taken directly from their corresponding bits in the 12-bit to IID mapping given by 0000:00ff:fe00:0XXX, where XXX are the 12 bits carried inline. Any remaining bits are zero.

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, the MAC layer supports payloads as big as 2031 octets and 1576 octets respectively. However when the channel condition is noisy, it is possible to configure smaller MTU at the MAC layer. If the configured MTU is smaller than 1280 octects, the fragmentation and reassembly defined in [RFC4944] MUST be used.

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].

5. Internet Connectivity Scenarios and Topologies

The PLC 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 [RFC8505]. IPv6 over PLC networks are built as tree, mesh or star according to the use cases. Generally, each PLC network has one PANC. In some cases, the PLC network can have alternate coordinators to replace the PANC when the PANC leaves the network for some reason. Note that the PLC topologies in this section are based on logical connectivity, not physical links. The term "PLC subnet" refers to a multilink subnet, in which the PLC devices share the same address prefix.

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 5). 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.

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

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

Figure 5: 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 6. 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.

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

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

Figure 6: 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 7), 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.

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

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

Figure 7: 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.

Malicious PLC devices could paralyze the whole network via DOS attacks, e.g., keep joining and leaving the network frequently, or multicast routing messages containing fake metrics. A device may also join a wrong or even malicious network, exposing its data to illegal users. Mutual authentication of network and new device can be conducted during the onboarding process of the new device. Methods include protocols such as [RFC7925] (exchanging pre-installed certificates over DTLS) , [I-D.ietf-6tisch-minimal-security] (which uses pre-shared keys), and [I-D.ietf-6tisch-dtsecurity-zerotouch-join] (which uses IDevID and MASA service). It is also possible to use EAP methods such as [I-D.ietf-emu-eap-noob] via transports like PANA [RFC5191]. No specific mechanism is specified by this document as an appropriate mechanism will depend upon deployment circumstances. The network encryption key appropriate for the layer-2 can also be acquired during the onboarding process.

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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IPv6 over Constrained Node Networks (6lo) Applicability & Use cases
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Abstract

This document describes the applicability of IPv6 over constrained node networks (6lo) and provides practical deployment examples. In addition to IEEE 802.15.4, various link layer technologies such as ITU-T G.9959 (Z-Wave), Bluetooth Low Energy, DECT-ULE, MS/TP, NFC, and PLC are used as examples. The document targets an audience who would like to understand and evaluate running end-to-end IPv6 over the constrained node networks for local or Internet connectivity.

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1. Introduction

Running IPv6 on constrained node networks presents challenges, due to the characteristics of these networks such as small packet size, low power, low bandwidth, low cost, and large number of devices, among others [RFC4919][RFC7228]. For example, many IEEE 802.15.4 variants [IEEE802154] exhibit a frame size of 127 octets, whereas IPv6 requires its underlying layer to support an MTU of 1280 bytes. Furthermore, those IEEE 802.15.4 variants do not offer fragmentation and reassembly functionality. Therefore, an appropriate adaptation layer supporting fragmentation and reassembly must be provided below IPv6. Also, the limited IEEE 802.15.4 frame size and low energy consumption requirements motivate the need for packet header compression. The IETF IPv6 over Low-Power WPAN (6LoWPAN) working group published a suite of specification that provide an adaptation layer to support IPv6 over IEEE 802.15.4 comprising the following functionality:

- o Fragmentation and reassembly, address autoconfiguration, and a frame format [RFC4944],
- o IPv6 (and UDP) header compression [RFC6282],
- o Neighbor Discovery Optimization for 6LoWPAN [RFC6775][RFC8505].

As Internet of Things (IoT) services become more popular, the IETF 6lo working group [IETF_6lo] has defined adaptation layer functionality to support IPv6 over various link layer technologies other than IEEE 802.15.4, such as Bluetooth Low Energy (Bluetooth LE), ITU-T G.9959 (Z-Wave), Digital Enhanced Cordless Telecommunications - Ultra Low Energy (DECT-ULE), Master-Slave/Token Passing (MS/TP), Near Field Communication (NFC), and Power Line Communication (PLC). The 6lo adaptation layers use a variation of the 6LoWPAN stack applied to each particular link layer technology.

The 6LoWPAN working group produced the document entitled "Design and Application Spaces for 6LoWPANs" [RFC6568], which describes potential application scenarios and use cases for low-power wireless personal area networks. The present document aims to provide guidance to an audience who are new to the IPv6 over constrained node networks (6lo) concept and want to assess its application to the constrained node network of their interest. This 6lo applicability document describes a few sets of practical 6lo deployment scenarios and use cases examples. In addition, it considers various network design space dimensions such as deployment, network size, power source, connectivity, multi-hop communication, traffic pattern, security level, mobility, and QoS requirements etc.

This document provides the applicability and use cases of 6lo, considering the following aspects:

- o It covers various IoT-related wired/wireless link layer technologies providing practical information of such technologies.

- It provides a general guideline on how the 6LoWPAN stack can be modified for a given L2 technology.

- Various 6lo use cases and practical deployment examples are described.

2. 6lo Link layer technologies

2.1. ITU-T G.9959

The ITU-T G.9959 Recommendation [G.9959] targets low-power Wireless Personal Area Networks (WPANs), and defines physical layer and link layer functionality. Physical layers of 9.6 kbit/s, 40 kbit/s and 100 kbit/s are supported. G.9959 defines how a unique 32-bit HomeID network identifier is assigned by a network controller and how an 8-bit NodeID host identifier is allocated to each node. NodeIDs are unique within the network identified by the HomeID. The G.9959 HomeID represents an IPv6 subnet that is identified by one or more IPv6 prefixes [RFC7428]. The ITU-T G.9959 can be used for smart home applications.

2.2. Bluetooth LE

Bluetooth LE was introduced in Bluetooth 4.0, enhanced in Bluetooth 4.1, and developed further in successive versions. Bluetooth SIG has also published the Internet Protocol Support Profile (IPSP). The IPSP enables discovery of IP-enabled devices and establishment of link-layer connection for transporting IPv6 packets. IPv6 over Bluetooth LE is dependent on both Bluetooth 4.1 and IPSP 1.0 or newer.

Many devices such as mobile phones, notebooks, tablets and other handheld computing devices which support Bluetooth 4.0 or subsequent versions also support the low-energy variant of Bluetooth. Bluetooth LE is also being included in many different types of accessories that collaborate with mobile devices. An example of a use case for a Bluetooth LE accessory is a heart rate monitor that sends data via the mobile phone to a server on the Internet [RFC7668]. A typical usage of Bluetooth LE is smartphone-based interaction with constrained devices. Bluetooth LE was originally designed to enable star topology networks. However, recent Bluetooth versions support the formation of extended topologies, and IPv6 support for mesh networks of Bluetooth LE devices is being developed [I-D.ietf-6lo-blemesh]

2.3. DECT-ULE

DECT-ULE is a low power air interface technology that is designed to support both circuit switched services, such as voice communication, and packet mode data services at modest data rate.

The DECT-ULE protocol stack consists of the physical layer operating at frequencies in the dedicated 1880 - 1920 MHz frequency band depending on the region and uses a symbol rate of 1.152 Mbps. Radio bearers are allocated by use of FDMA/TDMA/TDD techniques.

In its generic network topology, DECT is defined as a cellular network technology. However, the most common configuration is a star network with a single Fixed Part (FP) defining the network with a number of Portable Parts (PP) attached. The Medium Access Control (MAC) layer supports traditional DECT as this is used for services like discovery, pairing, security features etc. All these features have been reused from DECT.

The DECT-ULE device can switch to the ULE mode of operation, utilizing the new ULE MAC layer features. The DECT-ULE Data Link Control (DLC) provides multiplexing as well as segmentation and re-assembly for larger packets from layers above. The DECT-ULE layer also implements per-message authentication and encryption. The DLC layer ensures packet integrity and preserves packet order, but delivery is based on best effort.

The current DECT-ULE MAC layer standard supports low bandwidth data broadcast. However the usage of this broadcast service has not yet been standardized for higher layers [RFC8105]. DECT-ULE can be used for smart metering in a home.

2.4. MS/TP

MS/TP is a MAC protocol for the RS-485 [TIA-485-A] physical layer and is used primarily in building automation networks.

An MS/TP device is typically based on a low-cost microcontroller with limited processing power and memory. These constraints, together with low data rates and a small MAC address space, are similar to those faced in 6LoWPAN networks. MS/TP differs significantly from 6LoWPAN in at least three respects: a) MS/TP devices are typically mains powered, b) all MS/TP devices on a segment can communicate directly so there are no hidden node or mesh routing issues, and c) the latest MS/TP specification provides support for large payloads, eliminating the need for fragmentation and reassembly below IPv6.

MS/TP is designed to enable multidrop networks over shielded twisted pair wiring. It can support network segments up to 1000 meters in length at a data rate of 115.2 kbit/s or segments up to 1200 meters in length at lower bit rates. An MS/TP interface requires only a Universal Asynchronous Receiver-Transmitter (UART), an RS-485 [TIA-485-A] transceiver with a driver that can be disabled, and a 5 ms resolution timer. The MS/TP MAC is typically implemented in software.

Because of its superior "range" (~1 km) compared to many low power wireless data links, MS/TP may be suitable to connect remote devices (such as district heating controllers) to the nearest building control infrastructure over a single link [RFC8163].

2.5. NFC

NFC technology enables simple and safe two-way interactions between electronic devices, allowing consumers to perform contactless transactions, access digital content, and connect electronic devices with a single touch. NFC complements many popular consumer level wireless technologies, by utilizing the key elements in existing standards for contactless card technology (ISO/IEC 14443 A&B and JIS-X 6319-4).

Extending the capability of contactless card technology, NFC also enables devices to share information at a distance that is less than 10 cm with a maximum communication speed of 424 kbps. Users can share business cards, make transactions, access information from a smart poster or provide credentials for access control systems with a simple touch.

NFC's bidirectional communication ability is ideal for establishing connections with other technologies by the simplicity of touch. In addition to the easy connection and quick transactions, simple data sharing is also available [I-D.ietf-6lo-nfc]. NFC can be used for secure transfer in healthcare services.

2.6. PLC

PLC is a data transmission technique that utilizes power conductors as medium [I-D.ietf-6lo-plc]. Unlike other dedicated communication infrastructure, power conductors are widely available indoors and outdoors. Moreover, wired technologies cause less interference to the radio medium than wireless technologies and are more reliable than their wireless counterparts.

The below table shows some available open standards defining PLC.

PLC Systems	Frequency Range	Type	Data Rate	Distance
IEEE1901	<100MHz	Broadband	200Mbps	1000m
IEEE1901.1	<12MHz	PLC-IoT	10Mbps	2000m
IEEE1901.2	<500kHz	Narrowband	200kbps	3000m
G3-PLC	<500kHz	Narrowband	234kbps	3000m

Table 1: Some Available Open Standards in PLC

IEEE 1901 [IEEE1901] defines a broadband variant of PLC but is effective within short range. This standard addresses the requirements of applications with high data rate such as: Internet, HDTV, Audio, Gaming etc. Broadband operates on Orthogonal Frequency Division Multiplexing (OFDM) modulation.

IEEE 1902.1 [IEEE1901.1] defines a medium frequency band (less than 12 MHz) broadband PLC technology for smart grid applications based on OFDM. By achieving an extended communication range with medium speeds, this standard can be applied both in indoor and outdoor scenarios, such as Advanced Metering Infrastructure (AMI), street lighting, electric vehicle charging, smart city etc.

IEEE 1902.2 [IEEE1901.2] defines a narrowband variant of PLC with less data rate but significantly higher transmission range that could be used in an indoor or even an outdoor environment. It is applicable to typical IoT applications such as: Building Automation, Renewable Energy, Advanced Metering, Street Lighting, Electric Vehicle, Smart Grid etc. Moreover, IEEE 1901.2 standard is based on the 802.15.4 MAC sub-layer and fully endorses the security scheme defined in 802.15.4 [RFC8036]. A typical use case of PLC is smart grid.

G3-PLC [G3-PLC] is a narrowband PLC technology that is based on the ITU-T G.9903 Recommendation [G.9903]. The ITU-T G.9903 Recommendation contains the physical layer and data link layer specification for the G3-PLC narrowband OFDM power line communication transceivers, for communications via alternating current and direct current electric power lines over frequencies below 500 kHz.

2.7. Comparison between 6lo link layer technologies

In above clauses, various 6lo link layer technologies are described. The following table shows dominant parameters of each use case corresponding to the 6lo link layer technology.

	Z-Wave	BLE	DECT-ULE	MS/TP	NFC	PLC
Usage	Home Auto-mation	Interact w/ Smart Phone	Meter Reading	Building Auto-mation	Health-care Service	Smart Grid
Topology & Subnet	L2-mesh or L3-mesh	Star & Mesh	Star No mesh	MS/TP No mesh	P2P L2-mesh	Star Tree Mesh
Mobility Requirement	No	Low	No	No	Moderate	No
Security Requirement	High + Privacy required	Partially	High + Privacy required	High + Authen. required	High	High + Encrypt. required
Buffering Requirement	Low	Low	Low	Low	Low	Low
Latency, QoS Requirement	High	Low	Low	High	High	Low
Data Rate	Infrequ-ent	Infrequ-ent	Infrequ-ent	Frequent	Small	Infrequ-ent
RFC # or Draft	RFC7428	RFC7668, ietf-6lo-blemesh	RFC8105	RFC8163	draft-ietf-6lo-nfc	draft-ietf-6lo-plc

Table 2: Comparison between 6lo link layer technologies

3. Guidelines for adopting IPv6 stack (6lo)

6lo aims at reusing and/or adapting existing 6LoWPAN functionality in order to efficiently support IPv6 over a variety of IoT L2 technologies. The following guideline targets new candidate constrained L2 technologies that may be considered for running a modified 6LoWPAN stack on top. The modification of 6LoWPAN stack should be based on the following:

- o Addressing Model: Addressing model determines whether the device is capable of forming IPv6 link-local and global addresses and what is the best way to derive the IPv6 addresses for the constrained L2 devices. L2-address-derived IPv6 addresses are specified in [RFC4944], but there exist implications for privacy. For global usage, a unique IPv6 address must be derived using an assigned prefix and a unique interface ID. [RFC8065] provides such guidelines. For MAC-derived IPv6 addresses, please refer to [RFC8163] for IPv6 address mapping examples. Broadcast and multicast support are dependent on the L2 networks. Most low-power L2 implementations map multicast to broadcast networks. So care must be taken in the design when to use broadcast and try to stick to unicast messaging whenever possible.

- o MTU Considerations: The deployment should consider packet maximum transmission unit (MTU) needs over the link layer and should consider if fragmentation and reassembly of packets are needed at the 6LoWPAN layer. For example, if the link layer supports fragmentation and reassembly of packets, then the 6LoWPAN layer may not need to support fragmentation/reassembly. In fact, for most efficiency, choosing a low-power link layer that can carry unfragmented application packets would be optimum for packet transmission if the deployment can afford it. Please refer to 6lo RFCs [RFC7668], [RFC8163], [RFC8105] for example guidance.

- o Mesh or L3-Routing: 6LoWPAN specifications provide mechanisms to support mesh routing at L2, a configuration called mesh-under [RFC6606]. It is also possible to use an L3 routing protocol in 6LoWPAN, an approach known as route-over. [RFC6550] defines RPL, a L3 routing protocol for low power and lossy networks using directed acyclic graphs. 6LoWPAN is routing-protocol-agnostic and does not specify any particular L2 or L3 routing protocol to use with a 6LoWPAN stack.

- o Address Assignment: 6LoWPAN developed a new version of IPv6 Neighbor Discovery [RFC4861][RFC4862]. 6LoWPAN Neighbor Discovery [RFC6775][RFC8505] inherits from IPv6 Neighbor Discovery for mechanisms such as Stateless Address Autoconfiguration (SLAAC) and Neighbor Unreachability Detection (NUD). A 6LoWPAN node is also expected to be an IPv6 host per [RFC8200] which means it should ignore consumed routing headers and Hop-by-Hop options; when operating in a RPL network [RFC6550], it is also beneficial to support IP-in-IP encapsulation [I-D.ietf-roll-useofrplinfo]. The 6LoWPAN node should also support [RFC8505] and use it as the default Neighbor Discovery method. It is the responsibility of the deployment to ensure unique global IPv6 addresses for Internet connectivity. For local-only connectivity IPv6 Unique Local Address (ULA) may be used. [RFC6775][RFC8505] specifies the 6LoWPAN border router (6LBR), which is responsible for prefix assignment to the 6LoWPAN network. A 6LBR can be connected to the Internet or to an enterprise network via one of the interfaces. Please refer to [RFC7668] and [RFC8105] for examples of address assignment considerations. In addition, privacy considerations [RFC8065] must be consulted for applicability. In certain scenarios, the deployment may not support IPv6 address autoconfiguration due to regulatory and business reasons and may choose to offer a separate address assignment service. Address Protection for 6LoWPAN Neighbor Discovery (AP-ND) [RFC8928] enables Source Address Validation [RFC6620] and protects the address ownership against impersonation attacks.

o Broadcast Avoidance: 6LoWPAN Neighbor Discovery aims at reducing the amount of multicast traffic of classical Neighbor Discovery, since IP-level multicast translates into L2 broadcast in many L2 technologies. 6LoWPAN Neighbor Discovery relies on a proactive registration to avoid the use of multicast for address resolution. It also uses a unicast method for Duplicate Address Detection (DAD), and avoids multicast lookups from all nodes by using non-onlink prefixes. Router Advertisements (RAs) are also sent in unicast, in response to Router Solicitations (RSs)

o Host-to-Router interface: 6lo has defined registration extensions for 6LoWPAN Neighbor Discovery [RFC8505]. This effort provides a host-to-router interface by which a host can request its router to ensure reachability for the address registered with the router. Note that functionality has been developed to ensure that such a host can benefit from routing services in a RPL network [I-D.ietf-roll-unaware-leaves]

o Proxy Neighbor Discovery: Further functionality also allows a device (e.g. an energy-constrained device that needs to sleep most of the time) to request proxy Neighbor Discovery services from a 6LoWPAN Backbone Router (6BBR) [RFC8505][RFC8929]. The latter federates a number of links into a multilink subnet.

o Header Compression: IPv6 header compression [RFC6282] is a vital part of IPv6 over low power communication. Examples of header compression over different link-layer specifications are found in [RFC7668], [RFC8163], [RFC8105]. A generic header compression technique is specified in [RFC7400]. For 6LoWPAN networks where RPL is the routing protocol, there exist 6LoWPAN header compression extensions which allow to compress also the RPL artifacts used when forwarding packets in the route-over mesh [RFC8138] [I-D.ietf-roll-turnon-rfc8138]

- Security and Encryption: Though 6LoWPAN basic specifications do not address security at the network layer, the assumption is that L2 security must be present. In addition, application-level security is highly desirable. The working groups [IETF_ace] and [IETF_core] should be consulted for application and transport level security. 6lo working group is working on address authentication [RFC8928] and secure bootstrapping is also being discussed at IETF. However, there may be different levels of security available in a deployment through other standards such as hardware-level security or certificates for initial booting process. Encryption is important if the implementation can afford it.

- Additional processing: [RFC8066] defines guidelines for ESC dispatch octets use in the 6LoWPAN header. An implementation may take advantage of ESC header to offer a deployment specific processing of 6LoWPAN packets.

4. 6lo Deployment Scenarios

4.1. Wi-SUN usage of 6lo in network layer

Wireless Smart Ubiquitous Network (Wi-SUN)[Wi-SUN] is a technology based on the IEEE 802.15.4g standard. Wi-SUN networks support star and mesh topologies, as well as hybrid star/mesh deployments, but these are typically laid out in a mesh topology where each node relays data for the network to provide network connectivity. Wi-SUN networks are deployed on both powered and battery-operated devices [RFC8376].

The main application domains targeted by Wi-SUN are smart utility and smart city networks. This includes, but is not limited to the following applications:

- Advanced Metering Infrastructure

- Distribution Automation

- Home Energy Management

- Infrastructure Management

- Intelligent Transportation Systems

- Smart Street Lighting

- Agriculture

- Structural health (bridges, buildings)

- Monitoring and Asset Management

- Smart Thermostats, Air Conditioning and Heat Controls

- Energy Usage Information Displays

The Wi-SUN Alliance Field Area Network (FAN) covers primarily outdoor networks, and its specification is oriented towards meeting the more rigorous challenges of these environments. It has the following features:

- Open standards based on IEEE802, IETF, TIA, ETSI

- Architecture based on an IPv6 frequency hopping wireless mesh network with enterprise-level security

- Simple infrastructure of low cost, low complexity

- Enhanced network robustness, reliability, and resilience to interference, due to high redundancy and frequency hopping

- Enhanced scalability, long range, and energy friendliness

- Supports multiple global license-exempt sub-GHz bands

- Multi-vendor interoperability

- Very low power modes in development permitting long term battery operation of network nodes

The Wi-SUN FAN specification defines an IPv6-based protocol suite including TCP/UDP, IPv6, 6lo adaptation layer, DHCPv6 for IPv6 address management, RPL, and ICMPv6.

4.2. Thread usage of 6lo in network layer

Thread is an IPv6-based networking protocol stack built on open standards, designed for smart home environments, and based on low-power IEEE 802.15.4 mesh networks. Because of its IPv6 foundation, Thread can support existing popular application layers and IoT platforms, provide end-to-end security, ease development and enable flexible and future-proof designs [Thread].

The Thread specification uses the IEEE 802.15.4 [IEEE802154] physical and MAC layers operating at 250 kbps in the 2.4 GHz band. The IEEE 802.15.4-2006 and IEEE 802.15.4-2015 versions of the specification are used by Thread.

Thread devices use 6LoWPAN, as defined in [RFC4944][RFC6282], for transmission of IPv6 Packets over IEEE 802.15.4 networks. Header compression is used within the Thread network and devices transmitting messages compress the IPv6 header to minimize the size of the transmitted packet. The mesh header is supported for link-layer (i.e., mesh under) forwarding. The mesh header as used in Thread also allows efficient end-to-end fragmentation of messages rather than the hop-by-hop fragmentation specified in [RFC4944]. Mesh under routing in Thread is based on a distance vector protocol in a full mesh topology.

4.3. G3-PLC usage of 6lo in network layer

G3-PLC [G3-PLC] is a narrowband PLC technology that is based on the ITU-T G.9903 Recommendation [G.9903]. G3-PLC supports multi-hop mesh network topology, and facilitates highly-reliable, long-range communication. With the abilities to support IPv6 and to cross transformers, G3-PLC is regarded as one of the next-generation narrowband PLC technologies. G3-PLC has got massive deployments over several countries, e.g. Japan and France.

The main application domains targeted by G3-PLC are smart grid and smart cities. This includes, but is not limited to the following applications:

- o Smart Metering
- o Vehicle-to-Grid Communication
- o Demand Response
- o Distribution Automation
- o Home/Building Energy Management Systems

- o Smart Street Lighting

- o Advanced Metering Infrastructure (AMI) backbone network

- o Wind/Solar Farm Monitoring

In the G3-PLC specification, the 6lo adaption layer utilizes the 6LoWPAN functions (e.g. header compression, fragmentation and reassembly). However, due to the different characteristics of the PLC media, the 6LoWPAN adaptation layer cannot perfectly fulfill the requirements [I-D.ietf-6lo-plc]. The ESC dispatch type is used in the G3-PLC to provide native mesh routing and bootstrapping functionalities [RFC8066].

4.4. Netricity usage of 6lo in network layer

The Netricity program in HomePlug Powerline Alliance [NETRICITY] promotes the adoption of products built on the IEEE 1901.2 low-frequency narrowband PLC standard, which provides for urban and long distance communications and propagation through transformers of the distribution network using frequencies below 500 kHz. The technology also addresses requirements that assure communication privacy and secure networks.

The main application domains targeted by Netricity are smart grid and smart cities. This includes, but is not limited to the following applications:

- o Utility grid modernization

- o Distribution automation

- o Meter-to-Grid connectivity

- o Micro-grids

- o Grid sensor communications

- o Load control

- o Demand response

- o Net metering

- o Street Lighting control

- o Photovoltaic panel monitoring

Netricity system architecture is based on the physical and MAC layers of IEEE 1901.2 PLC standard. Regarding the 6lo adaptation layer and IPv6 network layer, Netricity utilizes IPv6 protocol suite including 6lo/6LoWPAN header compression, DHCPv6 for IP address management, RPL routing protocol, ICMPv6, and unicast/multicast forwarding. Note that the L3 routing in Netricity uses RPL in non-storing mode with the MRHOF objective function based on the own defined Estimated Transmission Time (ETT) metric.

5. 6lo Use Case Examples

As IPv6 stacks for constrained node networks use a variation of the 6LoWPAN stack applied to each particular link layer technology, various 6lo use cases can be provided. In this section, various 6lo use cases which are based on different link layer technologies are described.

5.1. Use case of ITU-T G.9959: Smart Home

Z-Wave is one of the main technologies that may be used to enable smart home applications. Born as a proprietary technology, Z-Wave was specifically designed for this particular use case. Recently, the Z-Wave radio interface (physical and MAC layers) has been standardized as the ITU-T G.9959 specification.

Example: Use of ITU-T G.9959 for Home Automation

Variety of home devices (e.g. light dimmers/switches, plugs, thermostats, blinds/curtains and remote controls) are augmented with ITU-T G.9959 interfaces. A user may turn on/off or may control home appliances by pressing a wall switch or by pressing a button in a remote control. Scenes may be programmed, so that after a given event, the home devices adopt a specific configuration. Sensors may also periodically send measurements of several parameters (e.g. gas presence, light, temperature, humidity, etc.) which are collected at a sink device, or may generate commands for actuators (e.g. a smoke sensor may send an alarm message to a safety system).

The devices involved in the described scenario are nodes of a network that follows the mesh topology, which is suitable for path diversity to face indoor multipath propagation issues. The multihop paradigm allows end-to-end connectivity when direct range communication is not possible. Security support is required, specially for safety-related communication. When a user interaction (e.g. a button press) triggers a message that encapsulates a command, if the message is lost, the user may have to perform further interactions to achieve the desired effect (e.g. turning off a light). A reaction to a user interaction will be perceived by the user as immediate as long as the reaction takes place within 0.5 seconds [RFC5826].

5.2. Use case of Bluetooth LE: Smartphone-based Interaction

The key feature behind the current high Bluetooth LE momentum is its support in a large majority of smartphones in the market. Bluetooth LE can be used to allow the interaction between the smartphone and surrounding sensors or actuators. Furthermore, Bluetooth LE is also the main radio interface currently available in wearables. Since a smartphone typically has several radio interfaces that provide Internet access, such as Wi-Fi or 4G, the smartphone can act as a gateway for nearby devices such as sensors, actuators or wearables. Bluetooth LE may be used in several domains, including healthcare, sports/wellness and home automation.

Example: Use of Bluetooth LE-based Body Area Network for fitness

A person wears a smartwatch for fitness purposes. The smartwatch has several sensors (e.g. heart rate, accelerometer, gyrometer, GPS, temperature, etc.), a display, and a Bluetooth LE radio interface. The smartwatch can show fitness-related statistics on its display. However, when a paired smartphone is in the range of the smartwatch, the latter can report almost real-time measurements of its sensors to the smartphone, which can forward the data to a cloud service on the Internet. 6lo enables this use case by providing efficient end-to-end IPv6 support. In addition, the smartwatch can receive notifications (e.g. alarm signals) from the cloud service via the smartphone. On the other hand, the smartphone may locally generate messages for the smartwatch, such as e-mail reception or calendar notifications.

The functionality supported by the smartwatch may be complemented by other devices such as other on-body sensors, wireless headsets or head-mounted displays. All such devices may connect to the smartphone creating a star topology network whereby the smartphone is the central component. Support for extended network topologies (e.g. mesh networks) is being developed as of the writing.

5.3. Use case of DECT-ULE: Smart Home

DECT is a technology widely used for wireless telephone communications in residential scenarios. Since DECT-ULE is a low-power variant of DECT, DECT-ULE can be used to connect constrained devices such as sensors and actuators to a Fixed Part, a device that typically acts as a base station for wireless telephones. Therefore, DECT-ULE is specially suitable for the connected home space in application areas such as home automation, smart metering, safety, healthcare, etc. Since DECT-ULE uses dedicated bandwidth, it avoids the coexistence issues suffered by other technologies that use e.g. ISM frequency bands.

Example: Use of DECT-ULE for Smart Metering

The smart electricity meter of a home is equipped with a DECT-ULE transceiver. This device is in the coverage range of the Fixed Part of the home. The Fixed Part can act as a router connected to the Internet. This way, the smart meter can transmit electricity consumption readings through the DECT-ULE link with the Fixed Part, and the latter can forward such readings to the utility company using Wide Area Network (WAN) links. The meter can also receive queries from the utility company or from an advanced energy control system controlled by the user, which may also be connected to the Fixed Part via DECT-ULE.

5.4. Use case of MS/TP: Building Automation Networks

The primary use case for IPv6 over MS/TP (6LoBAC) is in building automation networks. [BACnet] is the open international standard protocol for building automation, and MS/TP is defined in [BACnet] Clause 9. MS/TP was designed to be a low cost multi-drop field bus to inter-connect the most numerous elements (sensors and actuators) of a building automation network to their controllers. A key aspect of 6LoBAC is that it is designed to co-exist with BACnet MS/TP on the same link, easing the ultimate transition of some BACnet networks to native end-to-end IPv6 transport protocols. New applications for 6LoBAC may be found in other domains where low cost, long distance, and low latency are required. Note that BACnet comprises various networking solutions other than MS/TP, including the recently emerged BACnet IP. However, the latter is based on high speed Ethernet infrastructure, and thus it falls outside of the constrained node network scope.

Example: Use of 6LoBAC in Building Automation Networks

The majority of installations for MS/TP are for "terminal" or "unitary" controllers, i.e. single zone or room controllers that may connect to HVAC or other controls such as lighting or blinds. The economics of daisy-chaining a single twisted-pair between multiple devices is often preferred over home-run Cat-5 style wiring.

A multi-zone controller might be implemented as an IP router between a traditional Ethernet link and several 6LoBAC links, fanning out to multiple terminal controllers.

The superior distance capabilities of MS/TP (~1 km) compared to other 6lo media may suggest its use in applications to connect remote devices to the nearest building infrastructure. For example, remote pumping or measuring stations with moderate bandwidth requirements can benefit from the low cost and robust capabilities of MS/TP over other wired technologies such as DSL, and without the line-of-sight restrictions or hop-by-hop latency of many low cost wireless solutions.

5.5. Use case of NFC: Alternative Secure Transfer

In different applications, a variety of secured data can be handled and transferred. Depending on the security level of the data, different transfer methods can be alternatively selected.

Example: Use of NFC for Secure Transfer in Healthcare Services with Tele-Assistance

A senior citizen who lives alone wears one to several wearable 6lo devices to measure heartbeat, pulse rate, etc. The 6lo devices are densely installed at home for movement detection. A 6LBR at home will send the sensed information to a connected healthcare center. Portable base stations with LCDs may be used to check the data at home, as well. Data is gathered in both periodic and event-driven fashion. In this application, event-driven data can be very time-critical. In addition, privacy also becomes a serious issue in this case, as the sensed data is very personal.

While the senior citizen is provided audio and video healthcare services by a tele-assistance based on LTE connections, the senior citizen can alternatively use NFC connections to transfer the personal sensed data to the tele-assistance. Hidden hackers can overhear the data based on the LTE connection, but they cannot gather the personal data over the NFC connection.

5.6. Use case of PLC: Smart Grid

The smart grid concept is based on deploying numerous operational and energy measuring sub-systems in an electricity grid system. It comprises multiple administrative levels/segments to provide connectivity among these numerous components. Last mile connectivity is established over the Low Voltage (LV) segment, whereas connectivity over electricity distribution takes place in the High Voltage (HV) segment. Smart grid systems include Advanced Metering Infrastructure (AMI), Demand Response (DR), Home Energy Management System (HEMS), Wide Area Situational Awareness (WASA), among others.

Although other wired and wireless technologies are also used in Smart Grid, PLC enjoys the advantage of reliable data communication over electrical power lines that are already present, and the deployment cost can be comparable to wireless technologies. The 6lo-related scenarios for PLC mainly lie in the LV PLC networks with most applications in the area of Advanced Metering Infrastructure, Vehicle-to-Grid communications, in-home energy management and smart street lighting.

Example: Use of PLC for Advanced Metering Infrastructure

Household electricity meters transmit time-based data of electric power consumption through PLC. Data concentrators receive all the meter data in their corresponding living districts and send them to the Meter Data Management System (MDMS) through WAN network (e.g. Medium-Voltage PLC, Ethernet or GPRS) for storage and analysis. Two-way communications are enabled which means smart meters can do actions like notification of electricity charges according to the commands from the utility company.

With the existing power line infrastructure as communication medium, cost on building up the PLC network is naturally saved, and more importantly, labor operational costs can be minimized from a long-term perspective. Furthermore, this AMI application speeds up electricity charge, reduces losses by restraining power theft and helps to manage the health of the grid based on line loss analysis.

Example: Use of PLC (IEEE1901.1) for WASA in Smart Grid

Many sub-systems of Smart Grid require low data rate and narrowband variants (e.g., IEEE1901.1) of PLC fulfill such requirements. Recently, more complex scenarios are emerging that require higher data rates.

WASA sub-system is an appropriate example that collects large amount of information about the current state of the grid over wide area from electric substations as well as power transmission lines. The collected feedback is used for monitoring, controlling and protecting all the sub-systems.

6. IANA Considerations

There are no IANA considerations related to this document.

7. Security Considerations

Security considerations are not directly applicable to this document. For the use cases, the security requirements described in the protocol specifications apply.

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Appendix A. Design Space Dimensions for 6lo Deployment

The [RFC6568] lists the dimensions used to describe the design space of wireless sensor networks in the context of the 6LoWPAN working group. The design space is already limited by the unique characteristics of a LoWPAN (e.g. low power, short range, low bit rate). In [RFC6568], the following design space dimensions are described: Deployment, Network size, Power source, Connectivity, Multi-hop communication, Traffic pattern, Mobility, Quality of Service (QoS). However, in this document, the following design space dimensions are considered:

- Deployment/Bootstrapping: 6lo nodes can be connected randomly, or in an organized manner. The bootstrapping has different characteristics for each link layer technology.

- Topology: Topology of 6lo networks may inherently follow the characteristics of each link layer technology. Point-to-point, star, tree or mesh topologies can be configured, depending on the link layer technology considered.

- L2-Mesh or L3-Mesh: L2-mesh and L3-mesh may inherently follow the characteristics of each link layer technology. Some link layer technologies may support L2-mesh and some may not support.

- Multi-link subnet, single subnet: The selection of multi-link subnet and single subnet depends on connectivity and the number of 6lo nodes.

- Data rate: Typically, the link layer technologies of 6lo have low rate of data transmission. But, by adjusting the MTU, it can deliver higher upper layer data rate.

- Buffering requirements: Some 6lo use case may require more data rate than the link layer technology support. In this case, a buffering mechanism to manage the data is required.

- Security and Privacy Requirements: Some 6lo use case can involve transferring some important and personal data between 6lo nodes. In this case, high-level security support is required.

- Mobility across 6lo networks and subnets: The movement of 6lo nodes depends on the 6lo use case. If the 6lo nodes can move or moved around, a mobility management mechanism is required.

- Time synchronization requirements: The requirement of time synchronization of the upper layer service is dependent on the 6lo use case. For some 6lo use case related to health service, the measured data must be recorded with exact time and must be transferred with time synchronization.

- Reliability and QoS: Some 6lo use case requires high reliability, for example real-time service or health-related services.

- o Traffic patterns: 6lo use cases may involve various traffic patterns. For example, some 6lo use case may require short data length and random transmission. Some 6lo use case may require continuous data and periodic data transmission.

- o Security Bootstrapping: Without the external operations, 6lo nodes must have the security bootstrapping mechanism.

- o Power use strategy: to enable certain use cases, there may be requirements on the class of energy availability and the strategy followed for using power for communication [RFC7228]. Each link layer technology defines a particular power use strategy which may be tuned [RFC8352]. Readers are expected to be familiar with [RFC7228] terminology.

- o Update firmware requirements: Most 6lo use cases will need a mechanism for updating firmware. In these cases support for over the air updates are required, probably in a broadcast mode when bandwidth is low and the number of identical devices is high.

- o Wired vs. Wireless: Plenty of 6lo link layer technologies are wireless, except MS/TP and PLC. The selection of wired or wireless link layer technology is mainly dependent on the requirement of 6lo use cases and the characteristics of wired/ wireless technologies. For example, some 6lo use cases may require easy and quick deployment, whereas others may need a continuous source of power.

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