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RFC 9453
Applicability and Use Cases for IPv6 over Networks of Resource-constrained Nodes (6lo)

Abstract

This document describes the applicability of IPv6 over constrained-node networks (6lo) and provides practical deployment examples. In addition to IEEE Std 802.15.4, various link-layer technologies are used as examples, such as ITU-T G.9959 (Z-Wave), Bluetooth Low Energy (Bluetooth LE), Digital Enhanced Cordless Telecommunications - Ultra Low Energy (DECT-ULE), Master-Slave/Token Passing (MS/TP), Near Field Communication (NFC), and Power Line Communication (PLC). This 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.

Status of This Memo

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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, and large number of devices, among others [RFC4919] [RFC7228]. For example, many IEEE Std 802.15.4 variants [IEEE-802.15.4] exhibit a frame size of 127 octets, whereas IPv6 requires its underlying layer to support an MTU of 1280 bytes. Furthermore, those IEEE Std 802.15.4 variants do not offer fragmentation and reassembly functionality. (It is noted that IEEE Std 802.15.9-2021 provides a multiplexing and fragmentation layer for the IEEE Std 802.15.4 [IEEE-802.15.9].) Therefore, an appropriate adaptation layer supporting fragmentation and reassembly must be provided below IPv6. Also, the limited IEEE Std 802.15.4 frame size and low energy consumption requirements motivate the need for packet header compression. The IETF IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) Working Group published a suite of specifications that provides an adaptation layer to support IPv6 over IEEE Std 802.15.4 comprising the following functionalities:

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

As Internet of Things (IoT) services become more popular, the IETF has defined adaptation layer functionality to support IPv6 over various link-layer technologies other than IEEE Std 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 IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs)" [RFC6568], which describes potential application scenarios and use cases for LoWPANs. The present document aims to provide guidance to an audience that is 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-case examples. In addition, it considers various network design space dimensions, such as Deployment, Network Size, Power Source, Connectivity, Multi-Hop Communication, Traffic pattern, Mobility, and QoS requirements (see Appendix A).

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

- Various IoT-related wired or wireless link-layer technologies providing practical information about such technologies.
- General guidelines on how the 6LoWPAN stack can be modified for a given L2 technology.
- Various 6lo use cases and practical deployment examples.

Note that the use of "master" and "slave" have been retained in this document to align with use within the industry (e.g., [TIA-485-A] and [BACnet]).

2. 6lo Link-Layer Technologies

2.1. ITU-T G.9959

The ITU-T G.9959 Recommendation [G.9959] targets LoWPANs 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]. ITU-T G.9959 can be used for smart home applications, and the transmission range is 100 meters per hop.

2.2. Bluetooth LE

Bluetooth LE was introduced in Bluetooth 4.0, enhanced in Bluetooth 4.1, and developed further in successive versions. The data rate of Bluetooth LE is 125 kb/s, 500 kb/s, 1 Mb/s, 2 Mb/s; and max transmission range is around 100 meters (outdoors). The Bluetooth Special Interest Group (Bluetooth SIG) has also published the Internet Protocol Support Profile (IPSP). The IPSP enables discovery of IP-enabled devices and establishment of link-layer connections for transporting IPv6 packets. IPv6 over Bluetooth LE is dependent on both Bluetooth 4.1 [BTCorev5.4] and IPSP 1.0 [IPSP] or newer.

Many devices such as mobile phones, notebooks, tablets, and other handheld computing devices that 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 has been developed [RFC9159].

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 [TS102.939-1] [TS102.939-2].

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 Frequency-Division Multiplex (FDMA), Time-Division Multiple Access (TDMA), and Time-Division Duplex (TDD) techniques. The coverage distance is from 70 meters (indoors) to 600 meters (outdoors).

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 (PPs) attached. The Medium Access Control (MAC) layer supports classical DECT as this is used for services like discovery, pairing, and security features. All these features have been reused from DECT.

The DECT-ULE device can switch to the ULE mode of operation, utilizing the new Ultra Low Energy (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 issues or mesh routing issues.
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 long range (~1 km), MS/TP can be used 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 secure interactions between electronic devices, allowing consumers to perform contactless transactions, access digital content, and connect electronic devices with a single touch [LLCP-1.4]. The distance between sender and receiver is 10 cm or less. NFC complements many popular consumer-level wireless technologies by utilizing the key elements in existing standards for contactless card technology.

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 suitable for establishing connections with other technologies by the simplicity of touch. In addition to the easy connection and quick transactions, simple data sharing is available [RFC9428]. NFC can be used for secure transfer services where privacy is important.

2.6. PLC

PLC is a data transmission technique that utilizes power conductors as the medium [RFC9354]. 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 table below shows some available open standards defining PLC.

PLC Systems	Frequency Range	Type	Data Rate	Distance
IEEE 1901	< 100 MHz	Broadband	200 Mbps	1000 m
IEEE 1901.1	< 12 MHz	PLC-IoT	10 Mbps	2000 m
IEEE 1901.2	< 500 kHz	Narrowband	200 kbps	3000 m
G3-PLC	< 500 kHz	Narrowband	234 kbps	3000 m

Table 1: Some Available Open Standards in PLC

IEEE Std 1901 [IEEE-1901] defines a broadband variant of PLC, but it is only effective within short range. This standard addresses the requirements of high data rates such as the Internet, HDTV, audio, and gaming.

IEEE Std 1901.1 [IEEE-1901.1] defines a medium frequency band (less than 12 MHz) broadband PLC technology for smart grid applications based on Orthogonal Frequency Division Multiplexing (OFDM). By achieving an extended communication range with medium speeds, this standard can be applied in both indoor and outdoor scenarios, such as Advanced Metering Infrastructure (AMI), street lighting, electric vehicle charging, and a smart city.

IEEE Std 1901.2 [IEEE-1901.2] defines a narrowband variant of PLC with a lower data rate but a significantly higher transmission range that could be used in an indoor or even an outdoor environment. A typical use case of PLC is a 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 frequency bands below 500 kHz.

2.7. Comparison between 6lo Link-Layer Technologies

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

	Z-Wave	Bluetooth LE	DECT-ULE	MS/TP	NFC	PLC
Usage	Home Autom.	Interact w/ Smart Phone	Meter Reading	Building Autom.	Secure Transfer	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 Req.	No	Yes	No	No	Yes	No
Buffering Req.	Yes	Yes	Yes	Yes	Yes	Yes
Latency, QoS Req.	Yes	Yes	Yes	Yes	Yes	Yes
Frequent Tx Req.	No	No	No	Yes	No	No

	Z-Wave	Bluetooth LE	DECT-ULE	MS/TP	NFC	PLC
RFC	RFC 7428	RFC 7668 RFC 9159	RFC 8105	RFC 8163	RFC 9428	RFC 9354

Table 2: Comparison between 6lo Link-Layer Technologies

3. Guidelines for Adopting an IPv6 Stack (6lo)

6lo aims to reuse and/or adapt 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 the 6LoWPAN stack should be based on the following:

Addressing Model:
: The 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. IPv6 addresses that are derived from an L2 address are specified in [RFC4944], but there are implications for privacy. The reason is that the L2 address in 6lo link-layer technologies is a little short, and devices can become vulnerable to the various threats. 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, refer to [RFC8163] for 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 for when to use broadcast, trying to stick to unicast messaging whenever possible.

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 and reassembly. In fact, for greatest efficiency, choosing a low-power link layer that can carry unfragmented application packets would be optimal for packet transmission if the deployment can afford it. Please refer to 6lo RFCs [RFC7668], [RFC8163], and [RFC8105] for example guidance.

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, an 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.

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 an RPL network [RFC6550], it is also beneficial to support IP-in-IP encapsulation [RFC9008]. The 6LoWPAN node should also support the registration extensions defined in [RFC8505] and use the mechanism 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] and [RFC8505] specify 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 in [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-Protected Neighbor Discovery [RFC8928] enables source address validation [RFC6620] and protects the address ownership against impersonation attacks.

Broadcast Avoidance:
: 6LoWPAN Neighbor Discovery aims to reduce the amount of multicast traffic of classic Neighbor Discovery, since IP-level multicast translates into L2 broadcast in many L2 technologies [RFC6775]. 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).

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 [RFC9010].

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 RFC federates a number of links into a multi-link subnet.

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], and [RFC8105]. A generic header compression technique is specified in

[RFC7400]. For 6LoWPAN networks where RPL is the routing protocol, there are 6LoWPAN header compression extensions that allow compressing the RPL artifacts used when forwarding packets in the route-over mesh [RFC8138] [RFC9035].

Security and Encryption:
: Though 6LoWPAN basic specifications do not address security at the network layer, the assumption is that L2 security must be present. Nevertheless, care must be taken since specific L2 technologies may exhibit security gaps. Typically, 6lo L2 technologies (see Section 2) offer security properties such as confidentiality and/or message authentication. In addition, end-to-end security is highly desirable. Protocols such as DTLS/TLS, as well as Object Security, are being used in the constrained-node network domain [SEC-PROT-COMP]. The relevant IETF working groups should be consulted for application and transport level security. The IETF has worked on address authentication [RFC8928], and secure bootstrapping is also being discussed in the IETF. However, there may be other security mechanisms available in a deployment through other standards, such as hardware-level security or certificates for the initial booting process. In order to use security mechanisms, the implementation needs to be able to afford it in terms of processing capabilities and energy consumption.

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

4. 6lo Deployment Examples

4.1. Wi-SUN Usage of 6lo in Network Layer

Wireless Smart Ubiquitous Network (Wi-SUN) [Wi-SUN] is a technology based on IEEE Std 802.15.4g [IEEE-802.15.4]. 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 grid-powered and battery-operated devices [RFC8376].

The main application domains using Wi-SUN are smart utility and smart city networks. The Wi-SUN Alliance Field Area Network (FAN) primarily covers outdoor networks. The Wi-SUN FAN specification defines an IPv6-based protocol suite that includes TCP/UDP, IPv6, 6lo adaptation layer, DHCPv6 for IPv6 address management, RPL, and ICMPv6.

4.2. Thread Usage of 6lo in the 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 Std 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 designs [Thread].

The Thread specification uses the IEEE Std 802.15.4 [IEEE-802.15.4] physical and MAC layers operating at 250 kbps in the 2.4 GHz band.

Thread devices use 6LoWPAN, as defined in [RFC4944] and [RFC6282], for transmission of IPv6 packets over IEEE Std 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 using G3-PLC are smart grid and smart cities. This includes, but is not limited to, the following applications:

- smart metering
- vehicle-to-grid communication
- demand response
- distribution automation
- home/building energy management systems
- smart street lighting
- AMI backbone network
- 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 [RFC9354]. The ESC dispatch type is used in the G3-PLC to provide fundamental mesh routing and bootstrapping functionalities [RFC8066].

4.4. Netricity Usage of 6lo in the Network Layer

The Netricity program in the HomePlug Powerline Alliance [NETRICITY] promotes the adoption of products built on the IEEE Std 1901.2 low-frequency narrowband PLC standard [IEEE-1901.2], 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 using Netricity are smart grid and smart cities. This includes, but is not limited to, the following applications:

- utility grid modernization
- distribution automation
- meter-to-grid connectivity
- microgrids
- grid sensor communications
- load control
- demand response
- net metering
- street lighting control
- photovoltaic panel monitoring

The Netricity system architecture is based on the physical and MAC layers of IEEE Std 1901.2. Regarding the 6lo adaptation layer and an 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 (Minimum Rank with Hysteresis Objective Function) based on their 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 [G.9959].

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

> A 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 home appliances on and off, or the user may control them by pressing a wall switch or a button on a remote control. Scenes may be programmed so that the home devices adopt a specific configuration after a given event. Sensors may also periodically send measurements of several parameters (e.g., gas presence, light, temperature, humidity), 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 multi-hop paradigm allows end-to-end connectivity when direct range communication is not possible.

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 interaction between a 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 cellular, a 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 a Body Area Network Based on Bluetooth LE for Fitness

> A person wears a smartwatch for fitness purposes. The smartwatch has several sensors (e.g., heart rate, accelerometer, gyrometer, GPS, and temperature), 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 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 of this document.

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 (FP), a device that typically acts as a base station for wireless telephones. In this case, additionally, the FP must have a data network connection. Therefore, DECT-ULE is especially suitable for the connected home space in application areas such as home automation, smart metering, safety, and healthcare. Since DECT-ULE uses dedicated bandwidth, it avoids this coexistence issues suffered by other technologies that use, for example, Industrial, Scientific, and Medical (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 FP of the home. The FP 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 FP, 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 FP 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 interconnect 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 fundamental 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 it is 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 classical 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, 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

> An older adult who lives alone wears one to several wearable 6lo devices to measure heartbeat, pulse rate, etc. Other 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 displays 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 becomes a serious issue in this case, as the sensed data is very personal.

While the older adult is provided audio and video healthcare services by a tele-assistance based on cellular connections, the older adult can alternatively use NFC connections to transfer the personal sensed data to the tele-assistance. Hackers can overhear the data based on the cellular 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 subsystems in an electricity grid system. It comprises multiple administrative levels and segments to provide connectivity among these numerous components. Last mile connectivity is established over the Low-Voltage segment, whereas connectivity over electricity distribution takes place over the High-Voltage segment. Smart grid systems include AMI, Demand Response, Home Energy Management System, and Wide Area Situational Awareness (WASA), among others.

Although other wired and wireless technologies are also used in a smart grid, PLC benefits from 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 Low-Voltage PLC networks with most applications in the area of advanced metering infrastructure, vehicle-to-grid communications, in-home energy management, and smart street lighting.

Example: Use of PLC for AMI

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 through a WAN network (e.g., Medium-Voltage PLC, Ethernet, or General Packet Radio Service (GPRS)) for storage and analysis. Two-way communications are enabled, which means smart meters can perform actions like notification of electricity charges according to the commands from the utility company.

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

Example: Use of PLC (IEEE Std 1901.1) for WASA in a Smart Grid

Many subsystems of a smart grid require low data rates, and narrowband variants (e.g., IEEE Std 1901.1) of PLC fulfill such requirements. Recently, more complex scenarios are emerging that require higher data rates.

A WASA subsystem is an appropriate example that collects large amounts of information about the current state of the grid over a wide area from electric substations as well as power transmission lines. The collected feedback is used for monitoring, controlling, and protecting all the subsystems.

6. IANA Considerations

This document has no IANA actions.

7. Security Considerations

This document does not create security concerns in addition to those described in the Security Considerations sections of the 6lo adaptation layers considered in this document [RFC7428], [RFC7668], [RFC8105], [RFC8163], [RFC9159], [RFC9428], and [RFC9354].

Neighbor Discovery in 6lo links may be susceptible to threats as detailed in [RFC3756]. Mesh routing is expected to be common in some 6lo networks, such as ITU-T G.9959 networks, Bluetooth LE mesh networks, and PLC networks. This implies additional threats due to ad hoc routing as per [KW03]. Most of the L2 technologies considered in this document (i.e., ITU-T G.9959, Bluetooth LE, DECT-ULE, and PLC) support link-layer security. Making use of such provisions will alleviate the threats mentioned above. Note that NFC is often considered to offer intrinsic security properties due to its short link range. MS/TP does not support link-layer security, since in its original BACnet protocol stack, security is provided at the network layer; thus, alternative security functionality needs to be used for a 6lo-based protocol stack over MS/TP.

End-to-end communication is expected to be secured by means of common mechanisms, such as IPsec, DTLS/TLS, Object Security [RFC8613], and Ephemeral Diffie-Hellman Over COSE (EDHOC) [EDHOC].

The 6lo stack uses the IPv6 addressing model. The implications for privacy and network performance of using L2-address-derived IPv6 addresses need to be considered [RFC8065].

8. References

8.1. Normative References

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

[RFC4862] Thomson, S., Narten, T., and T. Jinmei, "IPv6 Stateless Address Autoconfiguration", RFC 4862, DOI 10.17487/RFC4862, September 2007, <https://www.rfc-editor.org/info/rfc4862>.

[RFC4919] Kushalnagar, N., Montenegro, G., and C. Schumacher, "IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs): Overview, Assumptions, Problem Statement, and Goals", RFC 4919, DOI 10.17487/RFC4919, August 2007, <https://www.rfc-editor.org/info/rfc4919>.

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

[RFC6568] Kim, E., Kaspar, D., and JP. Vasseur, "Design and Application Spaces for IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs)", RFC 6568, DOI 10.17487/RFC6568, April 2012, <https://www.rfc-editor.org/info/rfc6568>.

[RFC6606] Kim, E., Kaspar, D., Gomez, C., and C. Bormann, "Problem Statement and Requirements for IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) Routing", RFC 6606, DOI 10.17487/RFC6606, May 2012, <https://www.rfc-editor.org/info/rfc6606>.

[RFC7228] Bormann, C., Ersue, M., and A. Keranen, "Terminology for Constrained-Node Networks", RFC 7228, DOI 10.17487/RFC7228, May 2014, <https://www.rfc-editor.org/info/rfc7228>.

[RFC7400] Bormann, C., "6LoWPAN-GHC: Generic Header Compression for IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs)", RFC 7400, DOI 10.17487/RFC7400, November 2014, <https://www.rfc-editor.org/info/rfc7400>.

[RFC7428] Brandt, A. and J. Buron, "Transmission of IPv6 Packets over ITU-T G.9959 Networks", RFC 7428, DOI 10.17487/RFC7428, February 2015, <https://www.rfc-editor.org/info/rfc7428>.

[RFC7668] Nieminen, J., Savolainen, T., Isomaki, M., Patil, B., Shelby, Z., and C. Gomez, "IPv6 over BLUETOOTH(R) Low Energy", RFC 7668, DOI 10.17487/RFC7668, October 2015, <https://www.rfc-editor.org/info/rfc7668>.

[RFC8105] Mariager, P., Petersen, J., Ed., Shelby, Z., Van de Logt, M., and D. Barthel, "Transmission of IPv6 Packets over Digital Enhanced Cordless Telecommunications (DECT) Ultra Low Energy (ULE)", RFC 8105, DOI 10.17487/RFC8105, May 2017, <https://www.rfc-editor.org/info/rfc8105>.

[RFC8163] Lynn, K., Ed., Martocci, J., Neilson, C., and S. Donaldson, "Transmission of IPv6 over Master-Slave/Token-Passing (MS/TP) Networks", RFC 8163, DOI 10.17487/RFC8163, May 2017, <https://www.rfc-editor.org/info/rfc8163>.

[RFC8200] Deering, S. and R. Hinden, "Internet Protocol, Version 6 (IPv6) Specification", STD 86, RFC 8200, DOI 10.17487/RFC8200, July 2017, <https://www.rfc-editor.org/info/rfc8200>.

[RFC9159] Gomez, C., Darroudi, S.M., Savolainen, T., and M. Spoerk, "IPv6 Mesh over BLUETOOTH(R) Low Energy Using the Internet Protocol Support Profile (IPSP)", RFC 9159, DOI 10.17487/RFC9159, December 2021, <https://www.rfc-editor.org/info/rfc9159>.

[RFC9354] Hou, J., Liu, B., Hong, Y-G., Tang, X., and C. Perkins, "Transmission of IPv6 Packets over Power Line Communication (PLC) Networks", RFC 9354, DOI 10.17487/RFC9354, January 2023, <https://www.rfc-editor.org/info/rfc9354>.

8.2. Informative References

[BACnet] ASHRAE, "BACnet-A Data Communication Protocol for Building Automation and Control Networks (ANSI Approved)", ASHRAE Standard 135-2020, October 2020, <https://www.techstreet.com/standards/ashrae-135-2020?product_id=2191852>.

[BTCorev5.4] Bluetooth, "Core Specification Version 5.4", January 2012, <https://www.bluetooth.com/specifications/specs/core-specification-5-4/>.

[EDHOC] Selander, G., Preuß Mattsson, J., and F. Palombini, "Ephemeral Diffie-Hellman Over COSE (EDHOC)", Work in Progress, Internet-Draft, draft-ietf-lake-edhoc-22, 25 August 2023, <https://datatracker.ietf.org/doc/html/draft-ietf-lake-edhoc-22>.

[G.9903] ITU-T, "Narrowband orthogonal frequency division multiplexing power line communication transceivers for G3-PLC networks", ITU-T Recommendation G.9903, August 2017, <https://www.itu.int/rec/T-REC-G.9903-201708-I/en>.

[G.9959] ITU-T, "Short range narrow-band digital radiocommunication transceivers - PHY, MAC, SAR and LLC layer specifications", ITU-T Recommendation G.9959, January 2015, <https://www.itu.int/rec/T-REC-G.9959-201501-I/en>.

[G3-PLC] "G3-Alliance", <https://g3-plc.com>.

[IEEE-1901] IEEE, "IEEE Standard for Broadband over Power Line Networks: Medium Access Control and Physical Layer Specifications", DOI 10.1109/IEEESTD.2010.5678772, IEEE Std 1901-2010, December 2010, <https://standards.ieee.org/ieee/1901/4953/>.

[IEEE-1901.1] IEEE, "IEEE Standard for Medium Frequency (less than 12 MHz) Power Line Communications for Smart Grid Applications", DOI 10.1109/IEEESTD.2018.8360785, IEEE Std 1901.1-2018, May 2018, <https://ieeexplore.ieee.org/document/8360785>.

[IEEE-1901.2] IEEE, "IEEE Standard for Low-Frequency (less than 500 kHz) Narrowband Power Line Communications for Smart Grid Applications", DOI 10.1109/IEEESTD.2013.6679210, IEEE Std 1901.2-2013, December 2013, <https://standards.ieee.org/ieee/1901.2/4833/>.

[IEEE-802.15.4] IEEE, "IEEE Standard for Low-Rate Wireless Networks", DOI 10.1109/IEEESTD.2020.9144691, IEEE Std 802.15.4-2020, July 2020, <https://standards.ieee.org/ieee/802.15.4/7029/>.

[IEEE-802.15.9] IEEE, "IEEE Standard for Transport of Key Management Protocol (KMP) Datagrams", DOI 10.1109/IEEESTD.2022.9690134, IEEE Std 802.15.9-2021, January 2022, <https://ieeexplore.ieee.org/document/9690134>.

[IPSP] Bluetooth, "Internet Protocol Support Profile 1.0", December 2014, <https://www.bluetooth.com/specifications/specs/internet-protocol-support-profile-1-0/>.

[KW03] Karlof, C. and D. Wagner, "Secure routing in wireless sensor networks: attacks and countermeasures", Volume 1, Issues 2-3, Pages 293-315, DOI 10.1016/S1570-8705(03)00008-8, September 2003, <https://doi.org/10.1016/S1570-8705(03)00008-8>.

[LLCP-1.4] NFC Forum, "Logical Link Control Protocol Technical Specification", Version 1.4, December 2022, <https://nfc-forum.org/build/specifications/logical-link-control-protocol-technical-specification/>.

[NETRICITY] Netricity, "The Netricity program addresses the need for long range powerline networking for outside-the-home, smart meter-to-grid, and industrial control applications", <https://www.netricity.org/>.

[RFC3756] Nikander, P., Ed., Kempf, J., and E. Nordmark, "IPv6 Neighbor Discovery (ND) Trust Models and Threats", RFC 3756, DOI 10.17487/RFC3756, May 2004, <https://www.rfc-editor.org/info/rfc3756>.

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

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

[RFC6620] Nordmark, E., Bagnulo, M., and E. Levy-Abegnoli, "FCFS SAVI: First-Come, First-Served Source Address Validation Improvement for Locally Assigned IPv6 Addresses", RFC 6620, DOI 10.17487/RFC6620, May 2012, <https://www.rfc-editor.org/info/rfc6620>.

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

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

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

[RFC8138] Thubert, P., Ed., Bormann, C., Toutain, L., and R. Cragie, "IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) Routing Header", RFC 8138, DOI 10.17487/RFC8138, April 2017, <https://www.rfc-editor.org/info/rfc8138>.

[RFC8352] Gomez, C., Kovatsch, M., Tian, H., and Z. Cao, Ed., "Energy-Efficient Features of Internet of Things Protocols", RFC 8352, DOI 10.17487/RFC8352, April 2018, <https://www.rfc-editor.org/info/rfc8352>.

[RFC8376] Farrell, S., Ed., "Low-Power Wide Area Network (LPWAN) Overview", RFC 8376, DOI 10.17487/RFC8376, May 2018, <https://www.rfc-editor.org/info/rfc8376>.

[RFC8505] Thubert, P., Ed., Nordmark, E., Chakrabarti, S., and C. Perkins, "Registration Extensions for IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) Neighbor Discovery", RFC 8505, DOI 10.17487/RFC8505, November 2018, <https://www.rfc-editor.org/info/rfc8505>.

[RFC8613] Selander, G., Preuß Mattsson, J., Palombini, F., and L. Seitz, "Object Security for Constrained RESTful Environments (OSCORE)", RFC 8613, DOI 10.17487/RFC8613, July 2019, <https://www.rfc-editor.org/info/rfc8613>.

[RFC8928] Thubert, P., Ed., Sarikaya, B., Sethi, M., and R. Struik, "Address-Protected Neighbor Discovery for Low-Power and Lossy Networks", RFC 8928, DOI 10.17487/RFC8928, November 2020, <https://www.rfc-editor.org/info/rfc8928>.

[RFC8929] Thubert, P., Ed., Perkins, C.E., and E. Levy-Abegnoli, "IPv6 Backbone Router", RFC 8929, DOI 10.17487/RFC8929, November 2020, <https://www.rfc-editor.org/info/rfc8929>.

[RFC9008] Robles, M.I., Richardson, M., and P. Thubert, "Using RPI Option Type, Routing Header for Source Routes, and IPv6-in-IPv6 Encapsulation in the RPL Data Plane", RFC 9008, DOI 10.17487/RFC9008, April 2021, <https://www.rfc-editor.org/info/rfc9008>.

[RFC9010] Thubert, P., Ed. and M. Richardson, "Routing for RPL (Routing Protocol for Low-Power and Lossy Networks) Leaves", RFC 9010, DOI 10.17487/RFC9010, April 2021, <https://www.rfc-editor.org/info/rfc9010>.

[RFC9035] Thubert, P., Ed. and L. Zhao, "A Routing Protocol for Low-Power and Lossy Networks (RPL) Destination-Oriented Directed Acyclic Graph (DODAG) Configuration Option for the 6LoWPAN Routing Header", RFC 9035, DOI 10.17487/RFC9035, April 2021, <https://www.rfc-editor.org/info/rfc9035>.

[RFC9428] Choi, Y., Ed., Hong, Y., and J. Youn, "Transmission of IPv6 Packets over Near Field Communication", RFC 9428, DOI 10.17487/RFC9428, July 2023, <https://www.rfc-editor.org/info/rfc9428>.

[SEC-PROT-COMP] Preuß Mattsson, J., Palombini, F., and M. Vučinić, "Comparison of CoAP Security Protocols", Work in Progress, Internet-Draft, draft-ietf-iotops-security-protocol-comparison-02, 11 April 2023, <https://datatracker.ietf.org/doc/html/draft-ietf-iotops-security-protocol-comparison-02>.

[Thread] Thread, "Resources", <https://www.threadgroup.org/Support>.

[TIA-485-A] TIA, "Electrical Characteristics of Generators and Receivers for Use in Balanced Digital Multipoint Systems", TIA-485-A, Revision of TIA-485, March 1998, <https://global.ihs.com/doc_detail.cfm?item_s_key=00032964>.

[TS102.939-1] ETSI, "Digital Enhanced Cordless Telecommunications (DECT); Ultra Low Energy (ULE); Machine to Machine Communications; Part 1: Home Automation Network (phase 1)", V1.2.1, ETSI-TS 102 939-1, March 2015, <https://www.etsi.org/deliver/etsi_ts/102900_102999/10293901/01.02.01_60/ts_10293901v010201p.pdf>.

[TS102.939-2] ETSI, "Digital Enhanced Cordless Telecommunications (DECT); Ultra Low Energy (ULE); Machine to Machine Communications; Part 2: Home Automation Network (phase 2)", V1.1.1, ETSI TS 102 939-2, March 2015, <https://www.etsi.org/deliver/etsi_ts/102900_102999/10293902/01.01.01_60/ts_10293902v010101p.pdf>.

[Wi-SUN] "Wi-SUN Alliance", <https://www.wi-sun.org>.

Appendix A. Design Space Dimensions for 6lo Deployment

[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 Section 2 of [RFC6568], the following design space dimensions are described: Deployment, Network Size, Power Source, Connectivity, Multi-Hop Communication, Traffic Pattern, Mobility, and 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.

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

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

Buffering Requirements:
: Some 6lo use case may require a higher data rate than the link-layer technology support. In this case, a buffering mechanism, telling the application to throttle its generation of data, and compression of the data are possible to manage the data.

Security and Privacy Requirements:
: Some 6lo use cases 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 be 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 use case. For some 6lo use cases related to health service, the measured data must be recorded with the exact time.

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

Traffic Patterns:
: 6lo use cases may involve various traffic patterns. For example, some 6lo use cases may require short data lengths and random transmission. Some 6lo use cases may require continuous data transmission and discontinuous data transmission.

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

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 that may be tuned [RFC8352]. Readers are expected to be familiar with the terminology found in [RFC7228].

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

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 requirements of the 6lo use cases and the characteristics of wired and wireless technologies.

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