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Analysis of IPv6 over LPWAN: design space and challenges
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Abstract

Connecting Low Power Wide Area Networks (LPWANs) to the Internet is expected to provide significant benefits to these networks in terms of interoperability, application deployment, and management, among others. However, the constraints of LPWANs, often more extreme than those of typical 6Lo(WPAN) technologies, constitute a challenge for the 6LoWPAN suite in order to enable IPv6 over LPWAN. Considering the typical characteristics of LPWAN technologies, this document analyzes the design space and challenges related with enabling IPv6 over LPWAN.

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1. Introduction

Low Power Wide Area Network (LPWAN) technologies define long range, low bit rate and low power wireless interfaces that are used for control and monitoring applications. Examples of LPWAN technologies include LoRa, SigFox, IEEE 802.15.4k LECIM, Weightless, etc. [I-D.minaburo-lp-wan-gap-analysis].

Connecting LPWANs to the Internet is expected to provide significant benefits to these networks in terms of interoperability, application deployment, and management, among others. Therefore, the support of IPv6 over LPWAN is a fundamental aspect to be examined for LPWAN Internet connectivity.

Several technologies that exhibit significant constraints in various dimensions have exploited the 6LoWPAN suite of specifications ([RFC4944][RFC6282][RFC6775]) to support IPv6 [I-D.hong-6lo-use-cases]. 6LoWPAN, which was originally designed for IEEE 802.15.4 networks, provides a frame format, address autoconfiguration, fragmentation, header compression, and optimized IPv6 neighbor discovery.

However, the constraints of LPWANs, often more extreme than those of typical 6Lo(WPAN) technologies, constitute a challenge for the 6LoWPAN suite in order to enable IPv6 over LPWAN. LPWANs are characterized by device constraints (in terms of processing capacity, memory, and energy availability), and specially, link constraints, such as i) very low layer two payload size (from ~10 to ~100 bytes), ii) very low bit rate (from ~10 bit/s to ~100 kbit/s), and iii) in some specific technologies, further message rate constraints (e.g. between ~0.1 message/minute and ~1 message/minute) due to regional regulations that limit the duty cycle.

In some cases the 6LoWPAN functionality may be used to enable IPv6 over specific LPWAN technologies (with the level of adaptation done in the IPv6 over foo documents produced by the IETF 6lo WG), maintaining good performance. However, in the most challenged LPWAN technologies and/or configurations, further optimization and/or tuning of the 6LoWPAN functionality is required for efficient operation. This document analyzes the design space and challenges of enabling IPv6 over LPWAN.

1.1. 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]

2. Protocol stack

In the design of an IPv6 over foo adaptation layer, if more than one layer (other than the physical layer) is supported by the target technology, a crucial decision is which lower layer will interface with the adaptation layer. The layer(s) below the adaptation layer must provide the functionality to enable a link, i.e. "a communication facility or medium over which nodes can communicate at the link layer, i.e., the layer immediately below IP" [RFC4861].

In addition to the above requirement, further aspects to consider in the mentioned decision include lower layer support of fragmentation (see Section 5), overhead, and the ability of multplexing upper layer protocols.

3. Network topology and device roles

As of the writing, LPWAN technologies typically follow the star topology, whereby the end devices are connected through a direct link with a central device. In that case, the end devices and the central device will act as 6LoWPAN Nodes (6LN) and 6LoWPAN Border Router

(6LBR), respectively. The 6LBR may provide Internet connectivity (see Figure 1).

4. IPv6 subnet model

As IPv6 over LPWAN is intended for constrained nodes, and for Internet of Things use cases and environments, the complexity of implementing a separate subnet on each link and routing between the subnets appears to be excessive. For LPWAN, the benefits of treating the collection of links of the network 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].

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

          <------ Subnet -----><-- IPv6 connection -->

                     to Internet
```

Figure 1: LPWAN connected to the Internet

In the multilink subnet model, link-local multicast communications can happen only within a single link; thus, 6LN-to-6LN communications using link-local addresses are not possible. 6LNs connected to the same 6LBR have to communicate with each other by using the shared prefix used on the subnet.

5. Address autoconfiguration

In the ambit of 6Lo(WPAN) technologies, traditionally, Interface Identifiers (IIDs) have been derived from link layer identifiers [RFC4944] . This allows optimizations such as header compression. Nevertheless, due to privacy concerns, LPWAN devices should not be configured to embed their link layer address in the IID by default (see Section 3.2.2 of [RFC4903], and [I-D.ietf-6man-default-iids]).

6. Fragmentation

IPv6 requires an MTU of 1280 bytes [RFC2460] . Therefore, given the low maximum payload size of LPWAN technologies, fragmentation is needed.

If a layer of an LPWAN technology supports fragmentation, proper analysis has to be carried out to decide whether the fragmentation functionality provided by the lower layer or fragmentation at the adaptation layer should be used. Otherwise, fragmentation functionality shall be used at the adaptation layer.

6LoWPAN defined a fragmentation mechanism and a fragmentation header to support the transmission of IPv6 packets over IEEE 802.15.4 networks [RFC4944] . While the 6LoWPAN fragmentation header is appropriate for IEEE 802.15.4-2003 (which has a frame payload size of 81-102 bytes), it is not suitable for several LPWAN technologies, many of which have a maximum payload size that is one order of magnitude below that of IEEE 802.15.4-2003. The overhead of the 6LoWPAN fragmentation header is high, considering the reduced payload size of LPWAN technologies and the limited energy availability of the devices using such technologies. Furthermore, its datagram offset field is expressed in increments of eight octets. In some LPWAN technologies, the 6LoWPAN fragmentation header plus eight octets from the original datagram exceeds the available space in the layer two payload. To overcome these limitations, an optimized 6LoWPAN fragmentation header for LPWAN has been defined in [I-D.gomez-lpwan-fragmentation-header].

7. Neighbor discovery

6LoWPAN Neighbor Discovery [RFC6775] defined optimizations to IPv6 Neighbor Discovery [RFC4861] , in order to adapt functionality of the latter for networks of devices using IEEE 802.15.4 or similar technologies. The optimizations comprise host-initiated interactions to allow for sleeping hosts, replacement of multicast-based address resolution for hosts by an address registration mechanism, multihop extensions for prefix distribution and duplicate address detection (note that these are not needed in a star topology network), and support for 6LoWPAN header compression.

6LoWPAN Neighor Discovery may be used in LPWAN networks. However, the relative overhead incurred will depend on the LPWAN technology used (and on its configuration, if appropriate). In certain LPWAN setups (with a maximum payload size above ~60 bytes, and duty-cycle-free or equivalent operation), an RS/RA/NS/NA exchange may be completed in a few seconds, without incurring packet fragmentation. In others (with a maximum payload size of ~10 bytes, and a message rate of ~0.1 message/minute), the same exchange may take a few hours, leading to severe fragmentation and consuming a significant amount of the available network resources. See Annex A for an analysis of the 6LoWPAN Neighbor Discovery message sizes.

6LoWPAN Neighbor Discovery behavior may be tuned through the use of appropriate values for the default Router Lifetime, the Valid Lifetime in the PIOs, and the Valid Lifetime in the 6CO, as well as the address Registration Lifetime.

The Router Lifetime, which is present in RAs, may be as high as 18.2 hours. The Valid Lifetime in the PIO indicates the time of validity of the prefix indicated in the PIO, and it is possible to encode a value of infinity for this lifetime. The Valid Lifetime in the 6CO, which indicates the time of validity of the related context for header compression, may be as high as 45 days. A 6LN should unicast an RS to the router before expiration of any of these lifetimes. On the other hand, the address Registration Lifetime determines the periodicity with which a 6LN has to perform address reregistration with the router, and may be as high as 45 days.

Therefore, 6LoWPAN Neighbor Discovery supports relatively high periods without generating messages (the shortest being the maximum Router Lifetime). However, there exists a trade-off between Neighbor Discovery message overhead and reactivity to network changes (potentially affecting network connectivity) that must be assessed. On the other hand, the most challenged LPWAN setups may require the definition of functionality beyond the limits of [RFC6775].

8. Header compression

[RFC6282] defines stateless and stateful header compression for 6LoWPAN networks. This functionality is highly required in LPWAN, given the extreme resource constraints of these networks.

[RFC6282] defines a two-byte base encoding. To enable context-based compression of global addresses, a further byte is needed to encode source and destination context. Such compression may cover prefixes or complete, 128-bit IPv6 addresses. In the most minimalistic case, assuming that the IPv6 header fields allow the maximum possible degree of compression, an IPv6 header comprising global IPv6 addresses may be compressed to a size of 3 bytes.

Contexts may be disseminated by using the 6CO in RA messages. Up to 16 contexts may be defined. However, note that each 6CO for a full IPv6 address context adds 24 bytes to the RA message (Annex A), which incurs an amount of overhead which is not negligible for certain LPWAN setups.

If the network follows the star topology, optimizations for header compression that leverage this type of network topology may be used (see section 3.2.4 of [RFC7668]).

9. Unicast and multicast mapping

In some LPWAN technologies, layer two multicast is not supported. In that case, if the network topology is a star, the solution and considerations of section 3.2.5 of [RFC7668] may be applied.

10. Security Considerations

TBD

11. Acknowledgments

In section 4, the authors have reused part of the content available in section 3.2.1 of RFC 7668, and would like to thank the authors of that specification.

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12. Annex A. RFC 6775 message size analysis

-- Router Solicitation (RS), without options: 8 bytes

-- Router Advertisement (RA), without options: 16 bytes

-- Neighbor Solicitation (NS), without options: 24 bytes

-- Neighbor Advertisement (NA), without options: 24 bytes

-- Source Link-Layer Address Option (SLLAO): 2 bytes + link layer address size (bytes)

-- Prefix Information Option (PIO): 16 bytes + prefix size (bytes)

-- 6LoWPAN Context Option (6CO): 8 bytes + context prefix size (bytes)

-- Address Registration Option (ARO): 16 bytes

For the following calculations, a Link Layer Address (LLA) of 4 bytes, a prefix of 8 bytes, and a context prefix of 16 bytes (for maximum compression) have been assumed. A single 6CO is assumed, as a minimalistic use of header compression. (Note: the Authoritative Border Router Option (ABRO) will not be present in networks that follow the star topology.)

Message sizes:

-- Size of RS with SLLAO = 14 bytes

-- Size of RA with SLLAO, PIO and 6CO = 62 bytes

-- Size of NS with ARO and SLLAO = 46 bytes

-- Size of NA + ARO = 40 bytes

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LP-WAN GAP Analysis
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Abstract

Low Power Wide Area Networks (LP-WAN) are different technologies covering different applications based on long range, low bandwidth and low power operation. The use of IETF protocols in the LP-WAN technologies should contribute to the deployment of a wide number of applications in an open and standard environment where actual technologies will be able to communicate. This document makes a survey of the principal characteristics of these technologies and covers a cross layer analysis on how to adapt and use the actual IETF protocols, but also the gaps for the integration of the IETF protocol stack in the LP-WAN technologies.

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1. Introduction

LP-WAN (Low-Power Wide Area Network) technologies are a kind of constrained and challenged networks [RFC7228]. They can operate in license-exempt bands to provide connectivity to a vast number of battery-powered devices requiring limited communications. If the existing pilot deployments have shown the huge potential and the industrial interest in their capabilities, the loose coupling with the Internet makes the device management and network operation complex. More importantly, LP-WAN devices are, as of today, with no IP capabilities. The goal is to adapt IETF defined protocols, addressing schemes and naming spaces to this constrained environment.

2. Problem Statement

The LP-WANs are large-scale constrained networks in the sense of [RFC7228] with the following characteristics:

- very small frame payload as low as 12 bytes. Typical traffic patterns are composed of a large majority of frames with payload size around 15 bytes and a small minority of up to 100 byte frames. Some nodes will exchange less than 10 frames per day.

- very low bandwidth, most LP-WAN technologies offer a throughput between 50 bit/s to 250 kbit/s, with a duty cycle of 0.1% to 10% on some ISM bands.

- high packet loss, which can be the result of bad transmission conditions or collisions between nodes.

- variable MTU for a link depending on the used L2 modulation.

- highly asymmetric and in some cases unidirectional links.

- ultra dense networks with thousands to tens of thousands of nodes.

- different modulations and radio channels.

- sleepy nodes to preserve energy.

In the terminology of [RFC7228], these characteristics put LP-WANs into the "challenged network" category where the IP connectivity has to be redefined or modified. Therefore, LP-WANs need to be considered as a separate class of networks. The intrinsic characteristics, current usages and architectures will allow the group to make and justify the design choices. Some of the desired properties are:

- o keep compatibility with current Internet:
  - * preserve the end-to-end communication principle.
  - * maintain independence from L2 technology.
  - * use or adapt protocols defined by IETF to this new environment that could be less responsive.
  - * use existing addressing spaces and naming schemes defined by IETF.
- o ensure the correspondence with the stringent LP-WAN requirements, such as:
  - * limited number of messages per device.
  - * small message size, with potentially no L2 fragmentation.
  - * RTTs potentially orders of magnitude bigger than existing constrained networks.
- o optimize the protocol stack in order to limit the number of duplicated functionalities; for instance acknowledgements should not be done at several layers.

3. Identified gaps in current IETF groups concerning LP-WANs

3.1. IPv6 and LP-WAN

IPv6 [RFC2460] has been designed to allocate addresses to all the nodes connected to the Internet. Nevertheless the 40 bytes of overhead introduced by the protocol are incompatible with the LP-WAN constraints. If IPv6 were used, several LP-WAN frames will be needed just to carry the header. Another limitation comes from the MTU limit, which is 1280 bytes required from the layer 2 to carry IPv6 packet [RFC1981]. This is a side effect of the PMTU discovery mechanism, which allows intermediary routers to send to the source an ICMP message (packet too big) to reduce the size. An attacker will be able to forge this message and reduce drastically the transmission performances. This limit allows to mitigate the impact of this attack.

IPv6 needs a configuration protocol (neighbor discovery protocol, NDP [RFC4861]) to learn network parameters, and the node relation with its neighbor. This protocol generates a regular traffic with a large message size that does not fit LP-WAN constraints.

3.2. 6LoWPAN, 6lo and LP-WAN

6LoWPAN only resolves the IPv6 constraints by drastically reducing IPv6 overhead to about 4 bytes for ND traffic, but the header compression is not better for an end-to-end communications using global addresses (up to 20 bytes). 6LoWPAN has been initially designed for IEEE 802.15.4 networks with a frame size up to 127 bytes and a throughput of up to 250 kb/s with no duty cycle regarding the usage of the network.

IEEE 802.15.4 is a CSMA/CA protocol which means that every unicast frame is acknowledged. Because IEEE 802.15.4 has its own reliability mechanism by retransmission, 6LoWPAN does not have reliable delivery. Some LP-WAN technologies do not provide such acknowledgements at L2 and would require other reliability mechanisms.

6lo extends the usage of 6LoWPAN to other technologies (BLE, DECT, ...), with similar characteristics to IEEE 802.15.4. The main constraint in these networks comes from the nature of the devices (constrained devices), whereas in LP-WANs it is the network itself that imposes the most stringent constraint.

Neighbor Discovery has to be optimized by reducing the message size, the periodic exchanges and removing multicast message for point-to-point exchanges with border router.

3.3. 6tisch and LP-WAN

TODO

Describe why 6tisch is complementary to LP-WAN

A key element of 6tisch is the use of synchronization to enable determinism. An LP-WAN may or may not support synchronization like the one used in 6tisch. The 6tisch solution is dedicated to mesh networks that operate using 802.15.4e with a deterministic slotted channel.

3.4. ROLL and LP-WAN

The LP-WANs considered by the WG are based on a star topology, which eliminates the need for routing. Future works may address additional use-cases which may require the adaptation of existing routing protocols or the definition of new ones. For the moment, the work done at the ROLL WG and other routing protocols are out of scope of the LP-WAN WG.

3.5. CORE and LP-WAN

TODO

CoRE provides a resource-oriented application intended to run on constrained IP networks. It may be necessary to adapt the protocols to take into account the duty cycling and the potentially extremely limited throughput. For example, some of the timers in CoAP may need to be redefined. Taking into account CoAP acknowledgements may allow the reduction of L2 acknowledgements.

3.6. Security and LP-WAN

ToDo

3.7. Mobility and LP-WAN

TODO

LP-WAN nodes can be mobile. However, LP-WAN mobility is different than the one studied in the context of Mobile IP. LP-WAN implies sporadic traffic and will rarely be used for high-frequency, real-time communications.

4. Annex A -- survey of LP-WAN technologies

Different technologies can be included under the LP-WAN acronym. The following list is the result of a survey among the first participant to the mailing-list. It cannot be exhaustive but is representative of the current trends.

Technology	range	Throughput	MAC MTU
LoRa	2-5 km urban <15 km suburban	0.3 to 50 kbps	256 B
SIGFOX	10 km urban 50 km rural	100 bps	12 B
IEEE802.15.4k LECIM	< 20 km LoS < 5 km NoLoS	1.5 bps to 128 kbps	16/24/ 32 B
IEEE802.15.4g SUN	2-3 km LoS	4.8 kbps to 800 kbps	2047 B
RPMA	65 km LoS 20 km NoLoS	up: 624kbps down: 156kbps mob: 2kbps	64 B
DASH-7	2 km	9 kbps 55.55 kbps 166.66 kbps	256 B
Weightless-w	5 km urban	1 kbps to 10 Mbps	min 10 B
Weightless-n	<5 km urban <30 km suburban	30 kbps to 100kbps	max 20 B
Weightless-p	> 2 km urban	up to 100kbps	
NB-LTE	< 15 km	< 150 kbps	< 200 B

Figure 1: Survey of LP-WAN technologies

The table Figure 1 gives some key performance parameters for some candidate technologies. The maximum MTU size must be taken carefully, for instance in LoRa, it take up to 2 sec to send a 50 Byte frame using the most robust modulation. In that case the theoretical limit of 256 B will be impossible to reach.

Most of the technologies listed in the Annex A work in the ISM band and may be used for private a public networks. Weightless-W uses white spaces in the TV spectrum and NB-LTE will use licensed channels. Some technologies include encryption at layer 2.

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