CHAPTER 9

IPv6 OVER LOW-POWER WPAN (6LoWPAN)

As we have seen at various points in this text, most (but certainly not all) IoT/M2M nodes have noteworthy design constraints. Developers make the case that the IEEE 802.15.4-2003 standard is very promising for the lower (physical and link) layers. As for higher layer functions, the goal is to utilize IP technology, specifically IPv6, considering the v6 capabilities and benefits described in Chapter 7. To that end, an IETF Working Group (WG) was chartered in 2005 to define IPv6 over IEEE 802.15.4, that is to say, IPv6 over low-power WPANs; the outcome is known as 6LoWPAN. Two initial deliverables were generated in 2007: (i) problem statement ("Goals and Assumptions") and (ii) format specification ("IPv6 over 802.15.4"). 6LoWPAN is now a widely accepted approach to run IP on 802.15.4 based on the just cited format specification. It is already supported in TinyOS, Contiki, and in standards such as ISA SP 100, ZigBee Smart Energy (SE) 2.0, and the IEEE 1451.5 standard for wireless transducers. The basic RFC makes 802.15.4 look like an IPv6 link; it provides basic encapsulation and efficient representation of packets smaller than 100 octets. Some highlights of this work are provided in this chapter. The material is abstracted and synthesized from the basic RFCs. The reader is referred to the original material for a more detailed description of the specifications.

Building the Internet of Things with IPv6 and MIPv6: The Evolving World of M2M Communications, First Edition. Daniel Minoli.

9.1 BACKGROUND/INTRODUCTION

The requirement for IPv6 connectivity in a LoWPAN is driven by the following (1):

- The many devices in a LoWPAN make network autoconfiguration and statelessness highly desirable; as we have seen, IPv6 offers ready solutions;
- The large number of devices poses the need for a large address space, well met by IPv6;
- Given the limited packet size of LoWPANs, the IPv6 address format allows subsuming of IEEE 802.15.4 addresses, if so desired;
- Given the limited packet size, headers for IPv6 and layers above must be compressed whenever possible; and
- Simple interconnectivity of the LoWPANs to other IP networks including the Internet.

The WG has completed two RFCs: (i) "*IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs): Overview, Assumptions, Problem Statement, and Goals*" (RFC 4919) that documents and discusses the problem space, and (ii) "*Transmission of IPv6 Packets over IEEE 802.15.4 Networks*" (RFC 4944) that defines the format for the adaptation between IPv6 and 802.15.4. 6LoWPAN has also worked closely with the routing over low-power and lossy networks (LLNs) (roll) WG, which is developing IPv6 routing solutions for LLNs. See Table 9.1 for a detailed listing of the 6LoWPAN family of documents and specifications.

Recent additional work items of the WG include the following (2):

1. Produce "6LoWPAN Bootstrapping and 6LoWPAN IPv6 ND Optimizations" to define limited extensions to IPv6 neighbor discovery (RFC 4861) for use specifically in low-power networks. This document defines how to bootstrap a 6LoWPAN network and explore ND optimizations such as reusing the structure of the 802.15.4 network (e.g., by using the coordinators) and reduce the need for multicast by having devices talk to coordinators (without creating a single point of failure or changing the semantics of the IPv6 ND multicasts).
2. Produce "6LoWPAN Improved Header Compression" to describe mechanisms to allow enhancements to the 6LoWPAN headers. Specifically, this document describes the compression of addresses that are not link local. Additionally, the document may include other enhancements or optimizations of the HC1 or HC2 6LoWPAN headers.
3. Produce "6LoWPAN Architecture" to describe the design and implementation of 6LoWPAN networks. This document covers the concepts of "Mesh Under" and "Route Over," 802.15.4 design issues such as operation with sleeping nodes, network components (both battery and line powered), addressing, and IPv4/IPv6 network connections.

TABLE 9.1 6LoWPAN Family of Documents and Specifications

	Title	Date	Status
Active Internet Drafts			
draft-ietf-6LoWPAN-btle-11	Transmission of IPv6 packets over Bluetooth low energy	2012-10-12	IESG evaluation: AD follow-up (for 106 days) Submitted to IESG for publication
RFCs			
RFC 4919 (draft-ietf-6LoWPAN-problem)	IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs): Overview, Assumptions, Problem Statement, and Goals	2007-08	RFC 4919 (informational) errata
RFC 4944 (draft-ietf-6LoWPAN-format)	Transmission of IPv6 packets over IEEE 802.15.4 networks	2007-09	RFC 4944 (proposed standard) updated by RFC 6282, RFC 6775
RFC 6282 (draft-ietf-6LoWPAN-hc)	Compression format for IPv6 datagrams over IEEE 802.15.4-based networks	2011-09	RFC 6282 (proposed standard)
RFC 6568 (draft-ietf-6LoWPAN-usecases)	Design and Application Spaces for IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs)	2012-04	RFC 6568 (informational)
RFC 6606 (draft-ietf-6LoWPAN-routing-requirements)	Problem Statement and Requirements for IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) Routing	2012-05	RFC 6606 (informational)
RFC 6775 (draft-ietf-6LoWPAN-nd)	Neighbor Discovery Optimization for IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs)	2012-11 (new)	RFC 6775 (proposed standard)
Related Documents/Active Internet Drafts			
draft-bormann-6LoWPAN-ghc-05	6LoWPAN Generic Compression of Headers and Header-like Payloads	2012-09-06	I-D exists
draft-bormann-6LoWPAN-roadmap-03	6LoWPAN Roadmap and Implementation Guide	2012-10-22	I-D exists
draft-schoenw-6LoWPAN-mib-01	Definition of Managed Objects for IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs)		

4. As a separate Internet Draft, "6LoWPAN Routing Requirements" is aimed at describing 6LoWPAN-specific requirements on routing protocols used in 6LoWPANs, addressing both the "route-over" and "mesh-under" approach.
5. Produce "Use Cases for 6LoWPAN" to define, for a small set of applications with sufficiently unique requirements, how 6LoWPANs can solve those requirements, and which protocols and configuration variants can be used for these scenarios. The use cases will cover protocols for transport, application layer, discovery, configuration, and commissioning.
6. Produce "6LoWPAN Security Analysis" to define the threat model of 6LoWPANs, to document the suitability of existing key management schemes, and to discuss bootstrapping/installation/commissioning/setup issues.

9.2 6LoWPANS GOALS

LoWPANs[1] in general and IEEE 802.15.4-2003-based systems in particular have design constraints that need to be taken into consideration when developing a protocol stack. These constraints fall into two categories:

- Communication constraints defined by the underlying personal area network (PAN):
  - Small packet size. Given that the maximum physical layer packet is 127 bytes, the resulting maximum frame size at the media access control layer is 102 octets. Link-layer security imposes further overhead, leaving 81 octets for data packets. Adding all layers for IP connectivity should still allow transmission in one frame, without incurring excessive fragmentation and reassembly. Furthermore "control/protocol packets" fit within a single 802.15.4 frame;
  - Support for both 16-bit short or IEEE 64-bit extended media access control addresses;
  - Low bandwidth. Data rates of 250 Kbps, 40 Kbps, and 20 Kbps for each of the currently defined physical layers (2.4 GHz, 915 MHz, and 868 MHz, respectively);
  - Topologies include star and mesh operation;
  - Other issues to address include limited configuration and management capabilities, need for service discovery, and need for security (confidentiality and integrity protection).
- System constraints driven by the intended application parameters:
  - Characteristic examples include low/battery power, low cost, low processing capabilities, small memory size, large population of devices, ad-hoc locations/logical topology, mobility, and unreliable nodal behaviors (e.g., due to uncertain radio connectivity, interference, sleep state, battery drain, device, etc.)

[1]This discussion is summarized and synthesized from Reference 1.

While many LoWPAN devices in a network are expected to have limited functionality (the "reduced function devices" or RFDs discussed in Chapter 6), other, more capable "full function devices" (FFDs) will also be present in the network. FFDs are expected to "aid" RFDs by providing functions such as network coordination, packet forwarding, interfacing with other types of networks, and so on. LoWPANs must support various topologies including mesh and star. Mesh topologies imply multihop routing to a desired destination. In this case, intermediate devices act as packet forwarders at the link layer (akin to routers at the network layer). Typically, these are "FFDs" that have more capabilities in terms of power, computation, etc. The requirements on the routing protocol are:

- Given the minimal packet size of LoWPANs, the routing protocol must impose low (or no) overhead on data packets.
- The routing protocols should have low routing overhead (low chattiness) balanced with topology changes and power conservation.
- The computation and memory requirements in the routing protocol should be minimal to satisfy the low-cost and low-power objectives. Thus, storage and maintenance of large routing tables is detrimental.
- Support for network topologies in which either FFDs or RFDs may be battery or mains powered. This implies the appropriate considerations for routing in the presence of sleeping nodes.

Table 9.2 summarizes IP Protocol considerations for LoWPANs as defined in RFC 4919.

9.3 TRANSMISSION OF IPv6 PACKETS OVER IEEE 802.15.4

RFC 4944[2] describes the frame format for transmission of IPv6 packets and the method of forming IPv6 link-local addresses and statelessly autoconfigured addresses on IEEE 802.15.4 networks. Additional specifications include a simple header compression scheme using shared context and provisions for packet delivery in IEEE 802.15.4 meshes.

IEEE 802.15.4 defines four types of frames: beacon frames, MAC command frames, acknowledgement frames, and data frames, as noted in Chapter 6. IPv6 packets must be carried on data frames. Data frames may optionally request that they be acknowledged. IPv6 packets will be carried in frames for which acknowledgements are requested so as to aid link-layer recovery. IEEE 802.15.4 networks can either be nonbeacon enabled or beacon enabled. 6LoWPAN (RFC 4944) does not require that IEEE networks run in beacon-enabled mode. In nonbeacon-enabled networks, data frames (including those carrying IPv6 packets) are sent via the contention-based channel access method of unslotted Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA). In nonbeacon-enabled networks, beacons are not used for

[2]This discussion is summarized and synthesized from Reference 3.

TABLE 9.2 IP Protocol Considerations for LoWPANs as Defined in RFC 4919 (Partial List)

Item	Issues and Approaches
Fragmentation and reassembly layer	The PDUs in IEEE 802.15.4-2003 may be as small as 81 bytes. This is far below the minimum IPv6 packet size of 1280 octets and consistent with Section 5 of the IPv6 specification in RFC 2460; a fragmentation and reassembly adaptation layer must be provided at the layer below IP
Header compression	In the worst case the maximum size available for transmitting IP packets over an IEEE 802.15.4 frame is 81 octets, and that the IPv6 header is 40 octets long (without optional headers); this leaves only 41 octets for upper-layer protocols, such as UDP and TCP. UDP uses 8 octets in the header and TCP uses 20 octets. This leaves 33 octets for data over UDP and 21 octets for data over TCP. Additionally, as pointed above, there is also a need for a fragmentation and reassembly layer, which will use even more octets leaving very few octets for data. Thus, if one were to use the protocols as is, it would lead to excessive fragmentation and reassembly, even when data packets are just 10s of octets long. This mandated the need for header compression. 6LoWPAN expects using existing header compression techniques, but, if necessary, specifies new ones
Address autoconfiguration	6LoWPAN needs to define methods for creating IPv6 stateless address autoconfiguration. Stateless autoconfiguration (as compared to stateful) is attractive for 6LoWPANs, because it reduces the configuration overhead on the hosts. There is a need for a method to generate an "interface identifier" from the EUI-64 assigned to the IEEE 802.15.4 device
Mesh routing protocol	A routing protocol to support a multihop mesh network is necessary. There is much published work on ad-hoc multihop routing for devices, but these protocols are designed to use IP-based addresses that have large overheads. For example, the ad-hoc on-demand distance vector (AODV) routing protocol described in RFC 3561 uses 48 octets for a route request based on IPv6 addressing. Given the packet-size constraints, transmitting this packet without fragmentation and reassembly may be difficult. Thus, care should be taken when using existing routing protocols (or designing new ones) so that the routing packets fit within a single IEEE 802.15.4 frame

synchronization; however, they are still useful for link-layer device discovery to aid in association and disassociation events. RFC 4944 recommends that beacons be configured so as to aid these functions.

As we noted in Chapter 6, IEEE 802.15.4 allows the use of either IEEE 64-bit extended addresses or (after an association event) 16-bit addresses unique within the PAN. 6LoWPAN/RFC 4944 supports both 64-bit extended addresses and 16-bit short addresses; however, the RFC imposes additional constraints (beyond those imposed by IEEE 802.15.4) on the format of the 16-bit short addresses. Short addresses are transient in nature and are assigned by the PAN coordinator function during an association event; hence their validity and uniqueness is limited by the lifetime of that association. It should also be noted that because of the scalability issues posed by such a centralized allocation and single point of failure at the PAN coordinator, deployers should carefully weigh the trade-offs (and implement the necessary mechanisms) of growing such networks based on short addresses.

RFC 4944 assumes that a PAN maps to a specific IPv6 link. Note that multicast is not supported natively in IEEE 802.15.4; hence, IPv6 level multicast packets must be carried as link-layer broadcast frames in IEEE 802.15.4 networks.

The maximum transmission unit (MTU) size for IPv6 packets over IEEE 802.15.4 is 1280 octets. However, a full IPv6 packet does not fit in an IEEE 802.15.4 frame. 802.15.4 protocol data units (PDUs) have different sizes depending on how much overhead is present. Starting from a maximum physical layer packet size of 127 octets (aMaxPHYPacketSize) and a maximum frame overhead of 25 (aMaxFrameOverhead), the resultant maximum frame size at the media access control layer is 102 octets. Link-layer security imposes further overhead, which in the maximum case (21 octets of overhead in the AES-CCM-128 case, versus 9 and 13 for AES-CCM-32 and AES-CCM-64, respectively) leaves only 81 octets available. This implies that fragmentation and reassembly adaptation layer must be provided at the layer below IP.

Furthermore, the IPv6 header is 40 octets long and this leaves only 41 octets for upper-layer protocols, such as UDP. The latter uses 8 octets in the header, which leaves only 33 octets for application data. Additionally, as just noted, there is a need for a fragmentation and reassembly layer, which will use even more octets.

The encapsulation formats defined in the RFC (also called the "LoWPAN encapsulation") are the payload in the IEEE 802.15.4 MAC PDU. The LoWPAN payload (e.g., an IPv6 packet) follows this encapsulation header.

All LoWPAN-encapsulated datagrams transported over IEEE 802.15.4 are prefixed by an encapsulation header stack. Each header in the header stack contains a header type followed by zero or more header fields. While in an IPv6 header, the stack would contain, in the following order, addressing, hop-by-hop options, routing, fragmentation, destination options, and finally payload; in a LoWPAN header, the analogous header sequence is mesh (layer 2) addressing, hop-by-hop options (including layer 2 broadcast/multicast), fragmentation, and finally payload. Figure 9.1 shows typical header stacks that may be used in a LoWPAN network.

When more than one LoWPAN header is used in the same packet, they must appear in the following order:

1. Mesh addressing header
2. Broadcast header
3. Fragmentation header

All protocol datagrams (e.g., IPv6, compressed IPv6 headers, etc.) are preceded by one of the valid LoWPAN-encapsulation headers, examples of which are given

```
                A LoWPAN-encapsulated IPv6 datagram

             +---------------+------------+---------+
             | IPv6 Dispatch | IPv6 Header | Payload |
             +---------------+------------+---------+


       A LoWPAN-encapsulated LOWPAN_HC1 compressed IPv6 datagram

              +--------------+-----------+---------+
              | HC1 Dispatch | HC1 Header | Payload |
              +--------------+-----------+---------+


A LoWPAN-encapsulated LOWPAN_HC1 compressed IPv6 datagram that requires mesh
                               addressing

   +-----------+-------------+--------------+------------+---------+
   | Mesh Type | Mesh Header | HC1 Dispatch | HC1 Header | Payload |
   +-----------+-------------+--------------+------------+---------+


 A LoWPAN-encapsulated LOWPAN_HC1 compressed IPv6 datagram that requires
                              fragmentation

   +-----------+-------------+--------------+------------+---------+
   | Frag Type | Frag Header | HC1 Dispatch | HC1 Header | Payload |
   +-----------+-------------+--------------+------------+---------+


A LoWPAN-encapsulated LOWPAN_HC1 compressed IPv6 datagram that requires both
                      mesh addressing and fragmentation

    +-------+-------+-------+-------+---------+---------+---------+
    | M Typ | M Hdr | F Typ | F Hdr | HC1 Dsp | HC1 Hdr | Payload |
    +-------+-------+-------+-------+---------+---------+---------+


A LoWPAN-encapsulated LOWPAN_HC1 compressed IPv6 datagram that requires both
mesh addressing and a broadcast header to support mesh broadcast/multicast:

    +-------+-------+-------+-------+---------+---------+---------+
    | M Typ | M Hdr | B Dsp | B Hdr | HC1 Dsp | HC1 Hdr | Payload |
    +-------+-------+-------+-------+---------+---------+---------+
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FIGURE 9.1 Typical header stacks that may be used in a LoWPAN network.

above. This allows uniform software treatment of datagrams without regard to the mode of their transmission.

The definition of LoWPAN headers, other than mesh addressing and fragmentation, consists of the dispatch value, the definition of the header fields that follow, and their ordering constraints relative to all other headers. Although the header stack structure provides a mechanism to address future demands on the LoWPAN adaptation layer, it is not intended to provide general-purpose extensibility.

Refer to the RFC 4944 as well as to the other RFCs and drafts identified in Table 9.1 for an extensive discussion of the 6LoWPAN technology.

REFERENCES

1. Kushalnagar N, Montenegro G, Schumacher C. RFC 4919: IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs): Overview, Assumptions, Problem Statement, and Goals. IETF, August 2007.
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3. Montenegro G, Kushalnagar N, Hui J, Culler, D. Transmission of IPv6 Packets over IEEE 802.15.4 Networks, RFC 4944, Updated by RFC 6282, RFC 6775 (was draft-ietf-6LoWPAN-format), September 2007.