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N. Kushalnagar
Intel Corp
G. Montenegro
Microsoft Corporation
C. Schumacher
Danfoss A/S

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IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs): Overview, Assumptions, Problem Statement, and Goals

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Abstract

This document describes the assumptions, problem statement, and goals for transmitting IP over IEEE 802.15.4 networks. The set of goals enumerated in this document form an initial set only.

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1. Introduction

Low-power wireless personal area networks (LoWPANs) comprise devices that conform to the IEEE 802.15.4-2003 standard by the IEEE [IEEE802.15.4]. IEEE 802.15.4 devices are characterized by short range, low bit rate, low power, and low cost. Many of the devices employing IEEE 802.15.4 radios will be limited in their computational power, memory, and/or energy availability.

This document gives an overview of LoWPANs and describes how they benefit from IP and, in particular, IPv6 networking. It describes LoWPAN requirements with regards to the IP layer and the above, and spells out the underlying assumptions of IP for LoWPANs. Finally, it describes problems associated with enabling IP communication with devices in a LoWPAN, and defines goals to address these in a prioritized manner. Admittedly, not all items on this list may be necessarily appropriate tasks for the IETF. Nevertheless, they are documented here to give a general overview of the larger problem. This is useful both to structure work within the IETF as well as to better understand how to coordinate with external organizations.

2. Overview

A LoWPAN is a simple low cost communication network that allows wireless connectivity in applications with limited power and relaxed throughput requirements. A LoWPAN typically includes devices that work together to connect the physical environment to real-world applications, e.g., wireless sensors. LoWPANs conform to the IEEE 802.15.4-2003 standard [IEEE802.15.4].

Some of the characteristics of LoWPANs are as follows:

1. 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, 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 81 octets for data packets.

2. Support for both 16-bit short or IEEE 64-bit extended media access control addresses.

3. 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).

4. Topologies include star and mesh operation.

5. Low power. Typically, some or all devices are battery operated.

6. Low cost. These devices are typically associated with sensors, switches, etc. This drives some of the other characteristics such as low processing, low memory, etc. Numerical values for "low" elided on purpose since costs tend to change over time.

7. Large number of devices expected to be deployed during the lifetime of the technology. This number is expected to dwarf the number of deployed personal computers, for example.

8. Location of the devices is typically not predefined, as they tend to be deployed in an ad-hoc fashion. Furthermore, sometimes the location of these devices may not be easily accessible. Additionally, these devices may move to new locations.

9. Devices within LoWPANs tend to be unreliable due to variety of reasons: uncertain radio connectivity, battery drain, device lockups, physical tampering, etc.

10. In many environments, devices connected to a LoWPAN may sleep for long periods of time in order to conserve energy, and are unable to communicate during these sleep periods.

The following sections take into account these characteristics in describing the assumptions, problems statement, and goals for LoWPANs, and, in particular, for 6LoWPANs (IPv6-based LoWPAN networks).

3. Assumptions

Given the small packet size of LoWPANs, this document presumes applications typically send small amounts of data. However, the protocols themselves do not restrict bulk data transfers.

LoWPANs, as described in this document, are based on IEEE 802.15.4-2003. It is possible that the specification may undergo changes in the future and may change some of the requirements mentioned above.

Some of these assumptions are based on the limited capabilities of devices within LoWPANs. As devices become more powerful, and consume less power, some of the requirements mentioned above may be somewhat relaxed.

While some LoWPAN devices are expected to be extremely limited (the so-called "Reduced Function Devices" or RFDs), more capable "Full Function Devices" (FFDs) will also be present, albeit in much smaller numbers. FFDs will typically have more resources and may be mains powered. Accordingly, FFDs will aid RFDs by providing functions such as network coordination, packet forwarding, interfacing with other types of networks, etc.

The application of IP technology is assumed to provide the following benefits:

1. The pervasive nature of IP networks allows use of existing infrastructure.

2. IP-based technologies already exist, are well-known, and proven to be working.

3. An admittedly non-technical but important consideration is that IP networking technology is specified in open and freely available specifications, which is favorable or at least able to be better understood by a wider audience than proprietary solutions.

4. Tools for diagnostics, management, and commissioning of IP networks already exist.

5. IP-based devices can be connected readily to other IP-based networks, without the need for intermediate entities like translation gateways or proxies.

4. Problems

Based on the characteristics defined in the overview section, the following sections elaborate on the main problems with IP for LoWPANs.

4.1. IP Connectivity

The requirement for IP connectivity within a LoWPAN is driven by the following:

1. The many devices in a LoWPAN make network auto configuration and statelessness highly desirable. And for this, IPv6 has ready solutions.

2. The large number of devices poses the need for a large address space, well met by IPv6.

3. Given the limited packet size of LoWPANs, the IPv6 address format allows subsuming of IEEE 802.15.4 addresses if so desired.

4. Simple interconnectivity to other IP networks including the Internet.

However, given the limited packet size, headers for IPv6 and layers above must be compressed whenever possible.

4.2. Topologies

LoWPANs must support various topologies including mesh and star.

Mesh topologies imply multi-hop 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 "full function devices" that have more capabilities in terms of power, computation, etc. The requirements on the routing protocol are:

1. Given the minimal packet size of LoWPANs, the routing protocol must impose low (or no) overhead on data packets, hopefully independently of the number of hops.

2. The routing protocols should have low routing overhead (low chattiness) balanced with topology changes and power conservation.

3. 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.

4. 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.

As with mesh topologies, star topologies include provisioning a subset of devices with packet forwarding functionality. If, in addition to IEEE 802.15.4, these devices use other kinds of network interfaces such as ethernet or IEEE 802.11, the goal is to seamlessly integrate the networks built over those different technologies. This, of course, is a primary motivation to use IP to begin with.

4.3. Limited Packet Size

Applications within LoWPANs are expected to originate small packets. Adding all layers for IP connectivity should still allow transmission in one frame, without incurring excessive fragmentation and reassembly. Furthermore, protocols must be designed or chosen so that the individual "control/protocol packets" fit within a single 802.15.4 frame. Along these lines, IPv6's requirement of sub-IP reassembly (see Section 5) may pose challenges for low-end LoWPAN devices that do not have enough RAM or storage for a 1280-octet packet.

4.4. Limited Configuration and Management

As alluded to above, devices within LoWPANs are expected to be deployed in exceedingly large numbers. Additionally, they are expected to have limited display and input capabilities. Furthermore, the location of some of these devices may be hard to reach. Accordingly, protocols used in LoWPANs should have minimal configuration, preferably work "out of the box", be easy to bootstrap, and enable the network to self heal given the inherent unreliable characteristic of these devices. The size constraints of the link layer protocol should also be considered. Network management should have little overhead, yet be powerful enough to control dense deployment of devices.

4.5. Service Discovery

LoWPANs require simple service discovery network protocols to discover, control and maintain services provided by devices. In some cases, especially in dense deployments, abstraction of several nodes to provide a service may be beneficial. In order to enable such features, new protocols may have to be designed.

4.6. Security

IEEE 802.15.4 mandates link-layer security based on AES, but it omits any details about topics like bootstrapping, key management, and security at higher layers. Of course, a complete security solution for LoWPAN devices must consider application needs very carefully. Please refer to the security consideration section below for a more detailed discussion and in-depth security requirements.

5. Goals

The goals mentioned below are general and not limited to IETF activities. As such, they may not only refer to work that can be done within the IETF (e.g., specification required to transmit IP, profile of best practices for transmitting IP packets, and associated upper level protocols, etc). They also point at work more relevant to other standards bodies (e.g., desirable changes to or profiles relevant to IEEE 802.15.4, W3C, etc). When the goals fall under the IETF's purview, they serve to point out what those efforts should strive to accomplish, regardless of whether they are pursued within one (or more) new (or existing) working groups. When the goals do not fall under the purview of the IETF, documenting them here serves as input to other organizations [LIAISON].

Note that a common underlying goal is to reduce packet overhead, bandwidth consumption, processing requirements, and power consumption.

The following are the goals according to priority for LoWPANs:

1. Fragmentation and Reassembly layer: As mentioned in the overview, the protocol data units may be as small as 81 bytes. This is obviously far below the minimum IPv6 packet size of 1280 octets, and in keeping with Section 5 of the IPv6 specification [RFC2460], a fragmentation and reassembly adaptation layer must be provided at the layer below IP.

2. Header Compression: Given that 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, like 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 points to the need for header compression. As there is much published and in-progress standardization work on header compression, the 6LoWPAN community needs to investigate using existing header compression techniques, and, if necessary, specify new ones.

3. Address Autoconfiguration: [6LoWPAN] specifies methods for creating IPv6 stateless address auto configuration. Stateless auto configuration (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 [EUI64] assigned to the IEEE 802.15.4 device.

4. Mesh Routing Protocol: A routing protocol to support a multi-hop mesh network is necessary. There is much published work on ad-hoc multi hop routing for devices. Some examples include [RFC3561], [RFC3626], [RFC3684], all experimental. Also, these protocols are designed to use IP-based addresses that have large overheads. For example, the Ad hoc On-Demand Distance Vector (AODV) [RFC3561] routing protocol 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.

5. Network Management: One of the points of transmitting IPv6 packets is to reuse existing protocols as much as possible. Network management functionality is critical for LoWPANs. However, management solutions need to meet the resource constraints as well as the minimal configuration and self-healing functionality described in Section 4.4. The Simple Network Management Protocol (SNMP) [RFC3410] is widely used for monitoring data sources and sensors in conventional networks. SNMP functionality may be translated "as is" to LoWPANs with the benefit to utilize existing tools. However, due to the memory, processing, and message size constraints, further investigation is required to determine if the use of SNMPv3 is suitable, or if an appropriate adaptation of SNMPv3 or use of different protocols is in order.

6. Implementation Considerations: It may be the case that transmitting IP over IEEE 802.15.4 would become more beneficial if implemented in a "certain" way. Accordingly, implementation considerations are to be documented.

7. Application and higher layer Considerations: As header compression becomes more prevalent, overall performance will depend even more on efficiency of application protocols. Heavyweight protocols based on XML such as SOAP [SOAP], may not be suitable for LoWPANs. As such, more compact encodings (and perhaps protocols) may become necessary. The goal here is to specify or suggest modifications to existing protocols so that

they are suitable for LoWPANs. Furthermore, application level interoperability specifications may also become necessary in the future and may thus be specified.

8. Security Considerations: Security threats at different layers must be clearly understood and documented. Bootstrapping of devices into a secure network could also be considered given the location, limited display, high density, and ad-hoc deployment of devices.

6. Security Considerations

IPv6 over LoWPAN (6LoWPAN) applications often require confidentiality and integrity protection. This can be provided at the application, transport, network, and/or at the link layer (i.e., within the 6LoWPAN set of specifications). In all these cases, prevailing constraints will influence the choice of a particular protocol. Some of the more relevant constraints are small code size, low power operation, low complexity, and small bandwidth requirements.

Given these constraints, first, a threat model for 6LoWPAN devices needs to be developed in order to weigh any risks against the cost of their mitigations while making meaningful assumptions and simplifications. Some examples for threats that should be considered are man-in-the-middle attacks and denial of service attacks.

A separate set of security considerations apply to bootstrapping a 6LoWPAN device into the network (e.g., for initial key establishment). This generally involves application level exchanges or out-of-band techniques for the initial key establishment, and may rely on application-specific trust models; thus, it is considered extraneous to 6LoWPAN and is not addressed in these specifications. In order to be able to select (or design) this next set of protocols, there needs to be a common model of the keying material created by the initial key establishment.

Beyond initial key establishment, protocols for subsequent key management as well as to secure the data traffic do fall under the purview of 6LoWPAN. Here, the different alternatives (TLS, IKE/IPsec, etc.) must be evaluated in light of the 6LoWPAN constraints.

One argument for using link layer security is that most IEEE 802.15.4 devices already have support for AES link-layer security. AES is a block cipher operating on blocks of fixed length, i.e., 128 bits. To encrypt longer messages, several modes of operation may be used. The earliest modes described, such as ECB, CBC, OFB and CFB provide only confidentiality, and this does not ensure message integrity. Other modes have been designed which ensure both confidentiality and

message integrity, such as CCM* mode. 6LoWPAN networks can operate in any of the previous modes, but it is desirable to utilize the most secure modes available for link-layer security (e.g., CCM*), and build upon it.

For network layer security, two models are applicable: end-to-end security, e.g., using IPsec transport mode, or security that is limited to the wireless portion of the network, e.g., using a security gateway and IPsec tunnel mode. The disadvantage of the latter is the larger header size, which is significant at the 6LoWPAN frame MTUs. To simplify 6LoWPAN implementations, it is beneficial to identify the relevant security model, and to identify a preferred set of cipher suites that are appropriate given the constraints.

7. Acknowledgements

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Authors' Addresses

Nandakishore Kushalnagar
Intel Corp

EMail: nandakishore.kushalnagar@intel.com

Gabriel Montenegro
Microsoft Corporation

EMail: gabriel.montenegro@microsoft.com

Christian Peter Pii Schumacher
Danfoss A/S

EMail: schumacher@danfoss.com

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