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Requirements for an update to 6LoWPAN ND
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Abstract

Work presented at the ROLL, 6lo, 6TiSCH and 6MAN Working Groups suggest that enhancements to the 6LoWPAN ND mechanism are now needed. This document elaborates on those requirements and suggests approaches to serve them.

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1. Introduction

A number of use cases, including the Industrial Internet, require a large scale deployment of sensors that can not be realized with wires and is only feasible over wireless Low power and Lossy Network (LLN) technologies. When simpler hub-and-spoke topologies are not sufficient for the expected throughput and density, mesh networks are deployed, which implies the routing of packets over the mesh, operated at either Layer-2 or Layer-3.

For routing over a mesh at layer-3, the IETF has designed the IPv6 Routing Protocol over LLN (RPL) [RFC6550].

To assign routable addresses, DHCPv6 is still a viable option in LLNs. However, the IETF standard that supports address assignment specifically for LLNs is 6LoWPAN ND, the Neighbor Discovery Optimization for Low-power and Lossy Networks [RFC6775]. 6LoWPAN ND was designed as a stand-alone mechanism separately from its IETF routing counterpart, the IPv6 Routing Protocol for Low power and Lossy Networks [RFC6550] (RPL), and the interaction between the 2 protocols was not defined.

The 6TiSCH WG is now considering an architecture [I-D.ietf-6tisch-architecture] whereby a 6LowPAN ND host could connect to the Internet via a RPL Network, but this requires additions to the 6LOWPAN ND protocol to support mobility and reachability in a secured and manageable environment.

At the same time, new work at 6MAN on Efficiency aware IPv6 Neighbor Discovery Optimizations [I-D.chakrabarti-nordmark-6man-efficient-nd] suggests that 6LoWPAN ND can be extended to other types of networks on top of the Low power and Lossy Networks (LLNs) for which it was already defined. The value of such extension is especially apparent in the case of mobile wireless devices, to reduce the multicast operations that are related to classical ND ([RFC4861], [RFC4862]) and plague the wireless medium. In this context also, there is a need for additions to 6LOWPAN ND.

The Optimistic Duplicate Address Detection [RFC4429] (ODAD) specification details how an address can be used before a Duplicate Address Detection (DAD) is complete, and insists that an address that is TENTATIVE should not be associated to a Source Link-Layer Address Option in a Neighbor Solicitation message. Applying this rule to 6LOWPAN ND implies another change to its specification.

In [I-D.richardson-6tisch--security-6top], the 6tisch working group considers the use of layer-2 security. It develops a network bootstrap protocol that provides secure link connections at the same rate that nodes are discovered. This approach needs the presence of a routing protocol to route packets from a joining node to a security providing node (e.g. a PCE or commissioning tool).

This document suggests a limited evolution to [RFC6775] so as to allow operation of a 6LoWPAN ND node while a routing protocol (in first instance RPL) is present and operational. It also suggests a more generalized use of the information in the ARO option of the ND messages outside the strict LLN domain, for instance over a converged backbone.

2. Terminology

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].

Readers are expected to be familiar with all the terms and concepts that are discussed in "Neighbor Discovery for IP version 6" [RFC4861], "IPv6 Stateless Address Autoconfiguration" [RFC4862], "IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs): Overview, Assumptions, Problem Statement, and Goals" [RFC4919],

Neighbor Discovery Optimization for Low-power and Lossy Networks [RFC6775] and "Transmission of IPv6 Packets over IEEE 802.15.4 Networks" [RFC4944].

Additionally, this document uses terminology from 6TiSCH [I-D.ietf-6tisch-terminology] and ROLL [RFC7102].

3. Overview

This document is mostly motivated by the work ongoing in the 6TiSCH working group. The 6TiSCH architecture [I-D.ietf-6tisch-architecture] draft explains the network architecture of a 6TiSCH network. This architecture is used for the remainder of this document.

The scope of the 6TiSCH Architecture is a Backbone Link that federates multiple LLNs (mesh) as a single IPv6 Multi-Link Subnet. Each LLN in the subnet is anchored at a Backbone Router (6BBR). The Backbone Routers interconnect the LLNs over the Backbone Link and emulate that the LLN nodes are present on the Backbone thus creating a so-called: Multi-Link Subnet. An LLN node can move freely from an LLN anchored at a Backbone Router to another LLN anchored at the same or a different Backbone Router inside the Multi-Link Subnet and conserve its addresses.

```
               ---+-------------------------
                  |          Plant Network
                  |
               +-----+
               |     | Gateway
               |     |
               +-----+
                  |
                  |    Backbone Link (with VLANs)
            +--------------------+------------------+
            |                    |                  |
         +-----+             +-----+             +-----+
         |     | Backbone    |     | Backbone    |     | Backbone
         |     | router      |     | router      |     | router
         +-----+             +-----+             +-----+
           | |                | | |                 |
           0 0                0 0 0      (6LBR == LLN border router)
        o o   o  o       o o   o  o  o         o  o  o  o o
       o  o o  o o       o   o  o  o  o     (6LR == LLN router)
       o   o  o  o          o    o  o             z
       o   o o               o  o                  z
              RPL Instances               (6LoWPAN Host == LLN host)
```

Figure 1: 6TiSCH architecture

The 6LBR is the border router that is placed between the LLN and nodes outside the LLN. The 6LBR is logically separated from the 6BBR that is used to connect the LLN to the backbone. The 6LBR can use Efficient ND as the interface to register an LLN node in its topology to the 6BBR for whatever operation the 6BBR performs, such as ND proxy operations, or injection in a routing protocol. It results that, as illustrated in Figure 2, the periodic signaling could start at the leaf node with 6LoWPAN ND, then would be routed to the 6LBR, and then with Efficient-ND to the 6BBR. Efficient ND being an adaptation of 6LoWPAN ND, it makes sense to keep those two homogeneous in the way they use the source and the target addresses in the Neighbor Solicitation (NS) messages for registration, as well as in the options that they use for that process.

```
    6LoWPAN host        6LR             6LBR            6BBR

         |                |               |                |
         |  6LoWPAN ND    |  6LoWPAN ND   | Efficient ND   | IPv6 ND
         |   LLN link     |  IPv6 route   |  IPv6 link     | Backbone
         |                |               |                |
         |  NS(ARO)       |               |                |
         |--------------->|               |                |
         | 6LoWPAN ND     | DAR (then DAO)|                |
         |                |-------------->|                |
         |                |               |  NS(ARO)       |
         |                |               |--------------->|
         |                |               |                | DAD
         |                |               |                |------>
         |                |               |                |
         |                |               |  NA(ARO)       |
         |                |               |<---------------|
         |                | DAC           |                |
         |                |<--------------|                |
         |  NA(ARO)       |               |                |
         |<---------------|               |                |
```

Figure 2: (Re-)Registration Flow over Multi-Link Subnet

As the network builds up, a LoWPAN host starts as a leaf to join the LLN, and may later turn into a 6LR, so as to accept other nodes to recursively join the LLN.

Section 5 of the 6TiSCH architecture [I-D.ietf-6tisch-architecture] provides more information on the need to update the protocols that sustain the requirements in the next section.

4. Requirements

4.1. Requirements Related to Mobility

Due to the unstable nature of LLN links, even in a LLN of immobile nodes a 6LoWPAN Node may change its point of attachment to a 6LR, say 6LR-a, and may not be able to notify 6LR-a. Consequently, 6LR-a may still attract traffic that it cannot deliver any more. When links to a 6LR change state, there is thus a need to identify stale states in a 6LR and restore reachability in a timely fashion.

Req1.1: Upon a change of point of attachment, connectivity via a new 6LR MUST be restored timely without the need to de-register from the previous 6LR.

Req1.2: For that purpose, the protocol MUST enable to differentiate between multiple registrations from one 6LoWPAN Node and registrations from different 6LoWPAN Nodes claiming the same address.

Req1.3: Stale states MUST be cleaned up in 6LRs.

Req1.4: A 6LoWPAN Node SHOULD also be capable to register its Address to multiple 6LRs, and this, concurrently.

4.2. Requirements Related to Routing Protocols

The point of attachment of a 6LoWPAN Node may be a 6LR in an LLN mesh. IPv6 routing in a LLN can be based on RPL, which is the routing protocol that was defined at the IETF for this particular purpose. Other routing protocols than RPL are also considered by Standard Defining Organizations (SDO) on the basis of the expected network characteristics. It is required that a 6LoWPAN Node attached via ND to a 6LR would need to participate in the selected routing protocol to obtain reachability via the 6LR.

Next to the 6LBR unicast address registered by ND, other addresses including multicast addresses are needed as well. For example a routing protocol often uses a multicast address to register changes to established paths. ND needs to register such a multicast address to enable routing concurrently with discovery.

Multicast is needed for groups. Groups MAY be formed by device type (e.g. routers, street lamps), location (Geography, RPL sub-tree), or both.

The Bit Index Explicit Replication (BIER) Architecture [I-D.wijnands-bier-architecture] proposes an optimized technique to enable multicast in a LLN with a very limited requirement for routing state in the nodes.

Related requirements are:

Req2.1: The ND registration method SHOULD be extended in such a fashion that the 6LR MAY advertise the Address of a 6LoWPAN Node over the selected routing protocol and obtain reachability to that Address using the selected routing protocol.

Req2.2: Considering RPL, the Address Registration Option that is used in the ND registration SHOULD be extended to carry enough information to generate a DAO message as specified in [RFC6550] section 6.4, in particular the capability to compute a DAOSequence and, as an option, a RPLInstanceID.

Req2.3: Multicast operations SHOULD be supported and optimized, for instance using BIER or MPL. Whether ND is appropriate for the registration to the 6BBR is to be defined, considering the additional burden of supporting the Multicast Listener Discovery Version 2 [RFC3810] (MLDv2) for IPv6.

4.3. Requirements Related to the Variety of Low-Power Link types

6LoWPAN ND [RFC6775] was defined with a focus on IEEE802.15.4 and in particular the capability to derive a unique Identifier from a globally unique MAC-64 address. At this point, the 6lo Working Group is extending the 6LoWPAN Header Compression (HC) [RFC6282] technique to other link types ITU-T G.9959 [I-D.brandt-6man-lowpanz], Master-Slave/Token-Passing [I-D.ietf-6lo-6lobac], DECT Ultra Low Energy [I-D.ietf-6lo-dect-ule], Near Field Communication [I-D.hong-6lo-ipv6-over-nfc], as well as IEEE1901.2 Narrowband Powerline Communication Networks [I-D.popa-6lo-6loplc-ipv6-over-ieee19012-networks] and BLUETOOTH(R) Low Energy [I-D.ietf-6lo-btle].

Related requirements are:

Req3.1: The support of the registration mechanism SHOULD be extended to more LLN links than IEEE 802.15.4, matching at least the LLN links for which an "IPv6 over foo" specification exists, as well as Low-Power Wi-Fi.

Req3.2: As part of this extension, a mechanism to compute a unique Identifier should be provided, with the capability to form a Link-Local Address that SHOULD be unique at least within the LLN connected to a 6LBR discovered by ND in each node within the LLN.

Req3.3: The Address Registration Option used in the ND registration SHOULD be extended to carry the relevant forms of unique Identifier.

Req3.4: The Neighbour Discovery should specify the formation of a site-local address that follows the security recommendations from [RFC7217].

4.4. Requirements Related to Proxy Operations

Duty-cycled devices may not be able to answer themselves to a lookup from a node that uses classical ND on a backbone and may need a proxy. Additionally, the duty-cycled device may need to rely on the 6LBR to perform registration to the 6BBR.

The ND registration method SHOULD defend the addresses of duty-cycled devices that are sleeping most of the time and not capable to defend their own Addresses.

Related requirements are:

Req4.1: The registration mechanism SHOULD enable a third party to proxy register an Address on behalf of a 6LoWPAN node that may be sleeping or located deeper in an LLN mesh.

Req4.2: The registration mechanism SHOULD be applicable to a duty-cycled device regardless of the link type, and enable a 6BBR to operate as a proxy to defend the registered Addresses on its behalf.

Req4.3: The registration mechanism SHOULD enable long sleep durations, in the order of multiple days to a month.

4.5. Requirements Related to Security

In order to guarantee the operations of the 6LoWPAN ND flows, the spoofing of the 6LR, 6LBR and 6BBRs roles should be avoided. Once a node successfully registers an address, 6LoWPAN ND should provide energy-efficient means for the 6LBR to protect that ownership even when the node that registered the address is sleeping.

In particular, the 6LR and the 6LBR then should be able to verify whether a subsequent registration for a given Address comes from the original node.

In a LLN it makes sense to base security on layer-2 security. During bootstrap of the LLN, nodes join the network after authorization by a Joining Assistant (JA) or a Commissioning Tool (CT). After joining nodes communicate with each other via secured links. The keys for the layer-2 security are distributed by the JA/CT. The JA/CT can be part of the LLN or be outside the LLN. In both cases it is needed that packets are routed between JA/CT and the joining node.

Related requirements are:

Req5.1: 6LoWPAN ND security mechanisms SHOULD provide a mechanism for the 6LR, 6LBR and 6BBR to authenticate and authorize one another for their respective roles, as well as with the 6LoWPAN Node for the role of 6LR.

Req5.2: 6LoWPAN ND security mechanisms SHOULD provide a mechanism for the 6LR and the 6LBR to validate new registration of authorized nodes. Joining of unauthorized nodes MUST be impossible.

Req5.3: 6LoWPAN ND security mechanisms SHOULD lead to small packet sizes. In particular, the NS, NA, DAR and DAC messages for a re-registration flow SHOULD NOT exceed 80 octets so as to fit in a secured IEEE802.15.4 frame.

Req5.4: Recurrent 6LoWPAN ND security operations MUST NOT be computationally intensive on the LoWPAN Node CPU. When a Key hash calculation is employed, a mechanism lighter than SHA-1 SHOULD be preferred.

Req5.5: The number of Keys that the 6LoWPAN Node needs to manipulate SHOULD be minimized.

Req5.6: The 6LoWPAN ND security mechanisms SHOULD enable CCM* for use at both Layer 2 and Layer 3, and SHOULD enable the reuse of security code that has to be present on the device for upper layer security such as TLS.

Req5.7: Public key and signature sizes SHOULD be minimized while maintaining adequate confidentiality and data origin authentication for multiple types of applications with various degrees of criticality.

Req5.8: Routing of packets should continue when links pass from the unsecured to the secured state.

Req5.9: 6LoWPAN ND security mechanisms SHOULD provide a mechanism for the 6LR and the 6LBR to validate whether a new registration for a given address corresponds to the same 6LoWPAN Node that registered it initially, and, if not, determine the rightful owner, and deny or clean-up the registration that is duplicate.

4.6. Requirements Related to Scalability

Use cases from Automatic Meter Reading (AMR, collection tree operations) and Advanced Metering Infrastructure (AMI, bi-directional communication to the meters) indicate the needs for a large number of LLN nodes pertaining to a single RPL DODAG (e.g. 5000) and connected to the 6LBR over a large number of LLN hops (e.g. 15).

Related requirements are:

Req6.1: The registration mechanism SHOULD enable a single 6LBR to register multiple thousands of devices.

Req6.2: The timing of the registration operation should allow for a large latency such as found in LLNs with ten and more hops.

5. Security Considerations

This specification expects that the link layer is sufficiently protected, either by means of IP security for the Backbone Link or MAC sublayer cryptography. In particular, it is expected that the LLN MAC provides secure unicast to/from the Backbone Router and secure broadcast from the Backbone Router in a way that prevents tampering with or replaying the RA messages. Still, Section 4.5 has a requirement for a mutual authentication and authorization for a role for 6LRs, 6LBRs and 6BBRs.

This documents also suggests in Appendix A.4 that a 6LoWPAN Node could form a single Unique Interface ID (CUID) based on cryptographic techniques similar to CGA. The CUID would be used as Unique Interface Identifier in the ARO option and new Secure ND procedures would be proposed to use it as opposed to the source IPv6 address to secure the binding between an Address and its owning Node, and enforce First/Come-First/Serve at the 6LBR.

6. IANA Considerations

This draft does not require an IANA action.

7. Acknowledgments

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Appendix A. Suggested Changes to Protocol Elements

A.1. ND Neighbor Solicitation (NS)

The NS message used for registration should use a source address that respects the rules in [RFC6775], [RFC4861], and [RFC4429] for DAD. The SLLA Option may be present but only if the address passed DAD, and it is used to allow the 6LR to respond as opposed to as a registration mechanism.

The address that is being registered is the target address in the NS message and the TLLA Option must be present.

A.2. ND Router Advertisement (RA)

[I-D.chakrabarti-nordmark-6man-efficient-nd] adds an 'E' bit in the Router Advertisement flag, as well as a new Registrar Address Option (RAO). These fields are probably pertinent to LLNs inclusion into a revised 6LoWPAN ND should be studied. If the new 6LoWPAN flows require a change of behaviour (e.g. registering the Target of the NS message) then the RA must indicate that the router supports the new capability, and the NS must indicate that the Target is registered as opposed to the Source in an unequivocal fashion.

There is some amount of duplication between the options in the RPL DIO [RFC6550] and the options in the ND RA messages. At the same time, there are a number of options, including the 6LoWPAN Context Option (6CO) [RFC6775], the MTU and the SLLA Options [RFC4861] that can only be found in the RA messages. Considering that these options are useful for a joining node, the recommendation would be to associate the RA messages to the join beacon, and make them rare when the network is stable. On the other hand, the DIO message is to be used as the propagated heartbeat of the RPL network and provide the sense of time and liveliness.

RAs should also be issued and the information therein propagated when a change occurs in the information therein, such as a router or a prefix lifetime.

A.3. RPL DODAG Information Object (DIO)

If the RPL root serves as 6LBR, it makes sense to add at least a bit of information in the DIO to signal so. A Registrar Address Option (RAO) may also be considered for addition.

A.4. ND Enhanced Address Registration Option (EARO)

The ARO option contains a Unique ID that is supposed to identify the device across multiple registrations. It is envisioned that the device could form a single CGA-based Unique Interface ID (CUID) to securely bind all of its addresses. The CUID would be used as Unique Interface Identifier in the ARO option and to form a Link-Local address that would be deemed unique regardless of the Link type. Provided that the relevant cryptographic material is passed to the 6LBR upon the first registration or on-demand at a later time, the 6LBR can validate that a Node is effectively the owner of a CUID, and ensure that the ownership of an Address stays with the CUID that registered it first.

This option is designed to be used with standard NS and NA messages between backbone Routers as well as between nodes and 6LRs over the LLN and between the 6LBR and the 6BBR over whatever IP link they use to communicate.

```
    0                   1                   2                   3
    0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    |     Type      |     Length    |    Status     | RPLInstanceID |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    |Res|P|N| IDS |T|      TID      |     Registration Lifetime     |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    |                                                               |
    ~         Unique Interface Identifier (variable length)         ~
    |                                                               |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 3: EARO

The representation above is based on [I-D.chakrabarti-nordmark-6man-efficient-nd]. Only the proposed changes from that specification are discussed below but the expectation is that 6LoWPAN ND and Efficient ND converge on the ARO format.

Status: 8-bit integer. A new value of 3 is suggested to indicate a rejection due to an obsolete TID, typically an indication of a movement.

RPLInstanceID: 8-bit integer. This field is set to 0 when unused. Otherwise it contains the RPLInstanceID for which this address is registered, as specified in RPL [RFC6550], and discussed in particular in section 3.1.2.

P: One bit flag. When the bit is set, the address being registered is Target of the NS as opposed to the Source, for instance to enable ND proxy operation.

N: One bit flag. Set if the device moved. If not set, the 6BBR will refrain from sending gratuitous NA(O) or other form of distributed ND cache clean-up over the backbone. For instance, the flag should be reset after the DAD operation upon address formation.

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