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Registration Extensions for 6LoWPAN Neighbor Discovery
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Abstract

This specification updates RFC 6775 - 6LoWPAN Neighbor Discovery, to clarify the role of the protocol as a registration technique, simplify the registration operation in 6LoWPAN routers, as well as to provide enhancements to the registration capabilities and mobility detection for different network topologies including the backbone routers performing proxy Neighbor Discovery in a low power network.

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1. Introduction

IPv6 Low-Power Lossy Networks (LLNs) support star and mesh topologies. For such networks, "Neighbor Discovery Optimization for IPv6 over Low-Power Wireless Personal Area Networks" (6LoWPAN ND) [RFC6775] defines a registration mechanism and a central registrar to assure unique addresses. The 6LoWPAN ND mechanism reduces the dependency of the IPv6 Neighbor Discovery Protocol (IPv6 ND) [RFC4861][RFC4862] on network-layer multicast and link-layer broadcast operations.

This specification updates 6LoWPAN ND to simplify and generalize registration in 6LoWPAN routers (6LRs). In particular, this specification modifies and extends the behavior and protocol elements of 6LoWPAN ND to enable the following actions:

- o Determine the freshest location in case of node mobility
- o Simplify the registration flow for Link-Local Addresses
- o Support of a Leaf Node in a Route-Over network
- o Proxy registration in a Route-Over network
- o Associate the registration with a variable-length Registration Ownership Verifier (ROVR)
- o Registration via an IPv6 ND proxy over a Backbone Link (6BBR)
- o Better support for privacy and temporary addresses

These features satisfy requirements as listed in Appendix B.

2. Terminology

2.1. BCP 14

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119][RFC8174] when, and only when, they appear in all capitals, as shown here.

2.2. References

In this document, readers will encounter terms and concepts that are discussed in the following documents:

- "Cryptographically Generated Addresses (CGA)" [RFC3972],

- "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],

- "Problem Statement and Requirements for IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) Routing" [RFC6606], and

- "Neighbor Discovery Optimization for Low-power and Lossy Networks" [RFC6775],

2.3. New Terms

Backbone Link: An IPv6 transit link that interconnects two or more Backbone Routers.

Backbone Router (6BBR): A logical network function in an IPv6 router that proxies the 6LoWPAN ND operations specified in this document to assure address uniqueness and other functions required so that multiple LLNs can operate as a single IPv6 network.

Binding: The association between an IP address, a MAC address, and other information about the node that owns the IP Address.

Registration: The process by which a 6LN registers an IPv6 Address with a 6LR in order to establish connectivity to the LLN. In a Route-Over network, a 6LBR may register the 6LN to the 6BBR.

Registered Node: The 6LN for which the registration is performed, and which owns the fields in the Extended ARO option.

Registering Node: The node that performs the registration; either the Registered Node or a proxy.

Registered Address: An address registered for the Registered Node.

RFC6775-only: An implementation, a type of node, or a message that behaves only as specified by [RFC6775], as opposed to the behavior specified in this document.

Route-Over network: A network for which connectivity provided at the IP layer.

updated: A 6LN, a 6LR, or a 6LBR that supports this specification, in contrast to an RFC6775-only device.

2.4. Subset of a 6LoWPAN Glossary

This document often uses the following acronyms:

6BBR: 6LoWPAN Backbone Router

6LBR: 6LoWPAN Border Router

6LN: 6LoWPAN Node

6LR: 6LoWPAN Router

6CIO: Capability Indication Option

EARO: (Extended) Address Registration Option -- (E)ARO

EDAR: (Extended) Duplicate Address Request -- (E)DAR

EDAC: (Extended) Duplicate Address Confirmation -- (E)DAC

DAD: Duplicate Address Detection

DODAG: Destination-Oriented Directed Acyclic Graph

LLN: Low-Power and Lossy Network

NA: Neighbor Advertisement

NCE: Neighbor Cache Entry

ND: Neighbor Discovery

NDP: Neighbor Discovery Protocol

NS: Neighbor Solicitation

ROVR: Registration Ownership Verifier (pronounced rover)

RPL: IPv6 Routing Protocol for LLNs (pronounced ripple) [RFC6550]

RA: Router Advertisement

RS: Router Solicitation

TID: Transaction ID (a sequence counter in the EARO)

3. Applicability of Address Registration Options

The Address Registration Option (ARO) in [RFC6775] facilitates Duplicate Address Detection (DAD) for hosts and populates Neighbor Cache Entries (NCEs) [RFC4861] in the routers. This reduces the reliance on multicast operations, which are often as intrusive as broadcast, in IPv6 ND operations (see [I-D.ietf-mboned-ieee802-mcast-problems]).

With this specification, a failed or useless registration can be rejected by a 6LR or a 6LBR for reasons other than address duplication. Examples include:

- the router having run out of space;
- a registration bearing a stale sequence number perhaps denoting a movement of the host after the registration was placed;
- a host misbehaving and attempting to register an invalid address such as the unspecified address [RFC4291];
- a host using an address that is not topologically correct on that link.

In such cases the host will receive an error to help diagnose the issue and may retry, possibly with a different address, and possibly registering to a different router, depending on the returned error. The ability to return errors to address registrations is not intended to be used to restrict the ability of hosts to form and use multiple addresses. Each host may form and register a number of addresses for enhanced privacy, using mechanisms such as "Privacy Extensions for Stateless Address Autoconfiguration (SLAAC) in IPv6" [RFC4941], and

SHOULD conform to "Host Address Availability Recommendations" [RFC7934].

In IPv6 ND [RFC4861], a router needs enough storage to hold NCEs for all directly connected addresses to which it is currently forwarding packets (unused entries may be flushed). In contrast, a router serving the Address Registration mechanism needs enough storage to hold NCEs for all the addresses that may be registered to it, regardless of whether or not they are actively communicating. The number of registrations supported by a 6LoWPAN Router (6LR) or 6LoWPAN Border Router (6LBR) MUST be clearly documented by the vendor and the dynamic use of associated resources SHOULD be made available to the network operator, e.g., to a management console. Network administrators need to ensure that 6LR/6LBRs in their network support the number and type of devices that can register to them, based on the number of IPv6 addresses that those devices require and their address renewal rate and behavior.

4. Extended ND Options and Messages

This specification does not introduce new options; it modifies existing options and updates the associated behaviors.

4.1. Extended Address Registration Option (EARO)

The Address Registration Option (ARO) is defined in section 4.1 of [RFC6775].

This specification introduces the Extended Address Registration Option (EARO) based on the ARO for use in NS and NA messages. The EARO includes a sequence counter called Transaction ID (TID) that is used to determine the latest location of a registering mobile device. A new 'T' flag indicates the presence of the TID field is populated and that the option is an EARO. A 6LN requests routing or proxy services from a 6LR using a new 'R' flag in the EARO.

The EUI-64 field is redefined and renamed ROVR in order to carry different types of information, e.g., cryptographic information of variable size. A larger ROVR size MAY be used if and only if backward compatibility is not an issue in the particular deployment. The length of the ROVR field expressed in units of 8 bytes is the Length of the option minus 1.

Section 5.1 discusses those changes in depth.

The format of the EARO is shown in Figure 1:

```
 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     |    Opaque     |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Rsvd | I |R|T|     TID       |     Registration Lifetime     |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
...             Registration Ownership Verifier                 ...
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 1: EARO Option Format

Option Fields:

Type: 33

Length: 8-bit unsigned integer. The length of the option in units of 8 bytes.

Status: 8-bit unsigned integer. Indicates the status of a registration in the NA response. MUST be set to 0 in NS messages. See Table 1 below.

Opaque: An octet opaque to ND; the 6LN MAY pass it transparently to another process. It MUST be set to zero when not used.

Rsvd (Reserved): This field is unused. It MUST be initialized to zero by the sender and MUST be ignored by the receiver.

I: Two-bit Integer: A value of zero indicates that the Opaque field carries an abstract index that is used to decide in which routing topology the address is expected to be injected. In that case, the Opaque field is passed to a routing process with the indication that it carries topology information, and the value of 0 indicates default. All other values of "I" are reserved and MUST NOT be used.

R: The Registering Node sets the 'R' flag to request reachability for the registered address, e.g., by advertising the address in a Route-Over routing protocol or proxying ND over a Backbone Link.

T: One-bit flag. Set if the next octet is used as a TID.

TID: One-byte integer; a Transaction ID that is maintained by the node and incremented with each transaction of one or more registrations performed at the same time to one or more respective 6LRs. This field MUST be ignored if the 'T' flag is not set.

Registration Lifetime: 16-bit integer; expressed in minutes. A value of 0 indicates that the registration has ended and that the associated state MUST be removed.

Registration Ownership Verifier (ROVR): Enables the correlation between multiple attempts to register a same IPv6 Address. The ROVR size MUST be 64 bits when backward compatibility is needed; otherwise the size MAY be 128, 192, or 256 bits.

Value	Description
0..2	As defined in [RFC6775]. Note: a Status of 1 ("Duplicate Address") applies to the Registered Address. If the Source Address conflicts with an existing registration, "Duplicate Source Address" MUST be used.
3	Moved: The registration failed because it is not the freshest. This Status indicates that the registration is rejected because another more recent registration was done, as indicated by a same ROVR and a more recent TID. One possible cause is a stale registration that has progressed slowly in the network and was passed by a more recent one. It could also indicate a ROVR collision.
4	Removed: The binding state was removed. This status MAY be placed in an NA(EARO) message that is sent as the rejection of a proxy registration to a Backbone Router, or in an asynchronous NA(EARO) at any time.
5	Validation Requested: The Registering Node is challenged for owning the Registered Address or for being an acceptable proxy for the registration. A registrar (6LR, 6LBR, 6BBR) MAY place this Status in asynchronous DAC or NA messages.
6	Duplicate Source Address: The address used as source of the NS(EARO) conflicts with an existing registration.
7	Invalid Source Address: The address used as source of the NS(EARO) is not a Link-Local Address.
8	Registered Address topologically incorrect: The address being registered is not usable on this link.
9	6LBR Registry saturated: A new registration cannot be accepted because the 6LBR Registry is saturated. Note: this code is used by 6LBRs instead of Status 2 when responding to a Duplicate Address message exchange and is passed on to the Registering Node by the 6LR.
10	Validation Failed: The proof of ownership of the registered address is not correct.

Table 1: EARO Status

4.2. Extended Duplicate Address Message Formats

The DAR and DAC messages share a common base format as defined in section 4.4 of [RFC6775]. Those messages enable information from the ARO to be transported over multiple hops. The DAR and DAC are extended as shown in Figure 2:

```
 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      |CodePfx|CodeSfx|          Checksum             |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|    Status     |     TID       |     Registration Lifetime     |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
...               Registration Ownership Verifier               ...
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+                                                               +
|                                                               |
+                       Registered Address                      +
|                                                               |
+                                                               +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 2: Duplicate Address Messages Format

Modified Message Fields:

Code: The ICMP Code [RFC4443] for Duplicate Address Messages is split in two 4-bit fields, the Code Prefix and the Code Suffix. The Code Prefix MUST be set to zero by the sender and MUST be ignored by the receiver. A non-null value of the Code Suffix indicates support for this specification. It MUST be set to 1 when operating in a backward-compatible mode, indicating a ROVR size of 64 bits. It MAY be 2, 3 or 4, denoting a ROVR size of 128, 192, and 256 bits, respectively.

TID: 1-byte integer; same definition and processing as the TID in the EARO as defined in Section 4.1. This field MUST be ignored if the ICMP Code is null.

Registration Ownership Verifier (ROVR): The size of the ROVR is known from the ICMP Code Suffix. This field has the same definition and processing as the ROVR in the EARO option as defined in Section 4.1.

4.3. New 6LoWPAN Capability Bits in the Capability Indication Option

This specification defines 5 new capability bits for use in the 6CIO, defined by [RFC7400] for use in IPv6 ND messages.

The "E" flag indicates that EARO can be used in a registration. A 6LR that supports this specification MUST set the "E" flag.

The "D" flag indicates that the 6LBR supports EDA Messages. A 6LR that learns the "D" flag from advertisements can then exchange EDAR and EDAC messages with the 6LBR, and it also sets the "D" flag as well as the "L" flag in the 6CIO in its own advertisements. In this way, 6LNs will be able to prefer registration with a 6LR that can make use of new 6LBR features.

The new "L", "B", and "P" flags, indicate whether a router is capable of acting as 6LR, 6LBR, and 6BBR, respectively. These flags are not mutually exclusive; an updated node can advertise multiple collocated functions.

```
 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 = 1  |     Reserved      |D|L|B|P|E|G|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                           Reserved                            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 3: New Capability Bits in the 6CIO

Option Fields:

Type: 36

L: Node is a 6LR.

B: Node is a 6LBR.

P: Node is a 6BBR.

E: Node supports registrations based on EARO.

D: 6LBR supports EDA messages.

5. Updating RFC 6775

The Extended Address Registration Option (EARO) (see Section 4.1) updates the ARO used within Neighbor Discovery NS and NA messages between a 6LN and its 6LR. Similarly, EDAR and EDAC update the DAR and DAC messages so as to transport the new information between 6LRs and 6LBRs across an LLN mesh.

The extensions to the ARO option are the Duplicate Address Request (DAR) and Duplicate Address Confirmation (DAC), used in the Duplicate Address messages. They convey the additional information all the way to the 6LBR. In turn the 6LBR may proxy the registration using IPv6 ND over a Backbone Link as illustrated in Figure 4. This specification avoids the Duplicate Address message flow for Link-Local Addresses in a Route-Over [RFC6606] topology (see Section 5.6).

```
     6LN              6LR             6LBR            6BBR
      |                |               |                |
      |   NS(EARO)     |               |                |
      |--------------->|               |                |
      |                | Extended DAR  |                |
      |                |-------------->|                |
      |                |               |                |
      |                |               | proxy NS(EARO) |
      |                |               |--------------->|
      |                |               |                | NS(DAD)
      |                |               |                | ------>
      |                |               |                | <wait>
      |                |               |                |
      |                |               | proxy NA(EARO) |
      |                |               |<---------------|
      |                | Extended DAC  |                |
      |                |<--------------|                |
      |   NA(EARO)     |               |                |
      |<---------------|               |                |
      |                |               |                |
```

Figure 4: (Re-)Registration Flow

This specification allows multiple registrations, including for privacy / temporary addresses and provides a mechanism to help clean up stale registration state as soon as possible, e.g., after a movement (see Section 7).

Section 5 of [RFC6775] specifies how a 6LN bootstraps an interface and locates available 6LRs. A Registering Node SHOULD register to a

6LR that supports this specification if one is found, as discussed in Section 6.1, instead of registering to an RFC6775-only one; otherwise the Registering Node operates in a backward-compatible fashion when attaching to an RFC6775-only 6LR.

5.1. Extending the Address Registration Option

The Extended ARO (EARO) updates the ARO and is backward compatible with the ARO if and only if the Length of the option is set to 2. Its format is presented in Section 4.1. More details on backward compatibility can be found in Section 6.

The Neighbor Solicitation (NS) and the ARO are modified as follows:

- o The Target Address in the NS containing the EARO is now the field that indicates the address that is being registered, as opposed to the Source Address field as specified in [RFC6775] (see Section 5.5). This change enables a 6LBR to use one of its addresses as source of the proxy-registration of an address that belongs to a LLN Node to a 6BBR. This change also avoids in most cases the use of an address as source address before it is registered.

- o The EUI-64 field in the ARO Option is renamed Registration Ownership Verifier (ROVR) and is not required to be derived from a MAC address (see Section 5.3).

- o The option Length MAY be different than 2 and take a value between 3 and 5, in which case the EARO is not backward compatible with an ARO. The increase of size corresponds to a larger ROVR field, so the size of the ROVR is inferred from the option Length.

- o A new Opaque field is introduced to carry opaque information in case the registration is relayed to another process, e.g., to be advertised by a routing protocol. A new "I" field provides a type for the opaque information, and indicates the other process to which the 6LN passes the opaque value. A value of Zero for I indicates topological information to be passed to a routing process if the registration is redistributed. In that case, a value of Zero for the Opaque field is backward-compatible with the reserved fields that are overloaded, and the meaning is to use the default topology.

- o This document specifies a new flag in the EARO, the 'R' flag. If the 'R' flag is set, the Registering Node requests the 6LR to ensure reachability for the Registered Address, e.g., by means of routing or proxying ND. Conversely, when it is not set, the 'R' flag indicates that the Registering Node is a router, and that it

will advertise reachability to the Registered Address via a routing protocol (such as RPL [RFC6550]).

- o A node that supports this specification MUST be provide a Transaction ID (TID) field in the EARO, and set the 'T' flag to indicate the presence of the TID (see Section 5.2).

- o Finally, this specification introduces new status codes to help diagnose the cause of a registration failure (see Table 1).

A 6LN that acts only as a host, when registering, MUST set the 'R' flag to indicate that it is not a router and that it will not handle its own reachability. A 6LR that manages its reachability SHOULD NOT set the 'R' flag; if it does, routes towards this router may be installed on its behalf and may interfere with those it advertises.

5.2. Transaction ID

The TID is a sequence number that is incremented by the 6LN with each re-registration to a 6LR. The TID is used to determine the freshness of the registration request. The network uses the most recent TID to determine the current (most recent known) location(s) of a moving 6LN. When a Registered Node is registered with multiple 6LRs in parallel, the same TID MUST be used. This enables the 6LBRs and/or 6BBRs to determine whether the registrations are the same, and to distinguish that situation from a movement (see section 4 of [I-D.ietf-6lo-backbone-router] and Section 5.7 below).

5.2.1. Comparing TID values

The operation of the TID is fully compatible with that of the RPL Path Sequence counter as described in the "Sequence Counter Operation" section of the "IPv6 Routing Protocol for Low-Power and Lossy Networks" [RFC6550] specification.

A TID is deemed to be fresher than another when its value is greater as determined by the operations detailed in this section.

The TID range is subdivided in a 'lollipop' fashion ([Perlman83]), where the values from 128 and greater are used as a linear sequence to indicate a restart and bootstrap the counter, and the values less than or equal to 127 used as a circular sequence number space of size 128 as in [RFC1982]. Consideration is given to the mode of operation when transitioning from the linear region to the circular region. Finally, when operating in the circular region, if sequence numbers are determined to be too far apart then they are not comparable, as detailed below.

A window of comparison, SEQUENCE_WINDOW = 16, is configured based on a value of 2^N, where N is defined to be 4 in this specification.

For a given sequence counter,

1. The sequence counter SHOULD be initialized to an implementation defined value which is 128 or greater prior to use. A recommended value is 240 (256 - SEQUENCE_WINDOW).

2. When a sequence counter increment would cause the sequence counter to increment beyond its maximum value, the sequence counter MUST wrap back to zero. When incrementing a sequence counter greater than or equal to 128, the maximum value is 255. When incrementing a sequence counter less than 128, the maximum value is 127.

3. When comparing two sequence counters, the following rules MUST be applied:

   1. When a first sequence counter A is in the interval [128..255] and a second sequence counter B is in [0..127]:

      1. If (256 + B - A) is less than or equal to SEQUENCE_WINDOW, then B is greater than A, A is less than B, and the two are not equal.

      2. If (256 + B - A) is greater than SEQUENCE_WINDOW, then A is greater than B, B is less than A, and the two are not equal.

      For example, if A is 240, and B is 5, then (256 + 5 - 240) is 21. 21 is greater than SEQUENCE_WINDOW (16), thus 240 is greater than 5. As another example, if A is 250 and B is 5, then (256 + 5 - 250) is 11. 11 is less than SEQUENCE_WINDOW (16), thus 250 is less than 5.

   2. In the case where both sequence counters to be compared are less than or equal to 127, and in the case where both sequence counters to be compared are greater than or equal to 128:

      1. If the absolute magnitude of difference between the two sequence counters is less than or equal to SEQUENCE_WINDOW, then a comparison as described in [RFC1982] is used to determine the relationships greater than, less than, and equal.

2. If the absolute magnitude of difference of the two sequence counters is greater than SEQUENCE_WINDOW, then a desynchronization has occurred and the two sequence numbers are not comparable.

4. If two sequence numbers are determined to be not comparable, i.e., the results of the comparison are not defined, then a node should give precedence to the sequence number that was most recently incremented. Failing this, the node should select the sequence number in order to minimize the resulting changes to its own state.

5.3. Registration Ownership Verifier (ROVR)

The ROVR field replaces the EUI-64 field of the ARO defined in [RFC6775]. It is associated in the 6LR and the 6LBR with the registration state. The ROVR can be a unique ID of the Registering Node, such as the EUI-64 address of an interface. This can also be a token obtained with cryptographic methods which can be used in additional protocol exchanges to associate a cryptographic identity (key) with this registration to ensure that only the owner can modify it later, if the proof-of-ownership of the ROVR can be obtained (more in Section 5.6). The scope of a ROVR is the registration of a particular IPv6 Address and it MUST NOT be used to correlate registrations of different addresses.

The ROVR can be of different types; the type is signaled in the message that carries the new type. For instance, the type can be a cryptographic string and used to prove the ownership of the registration as specified in "Address Protected Neighbor Discovery for Low-power and Lossy Networks" [I-D.ietf-6lo-ap-nd]. In order to support the flows related to the proof-of-ownership, this specification introduces new status codes "Validation Requested" and "Validation Failed" in the EARO.

Note on ROVR collision: different techniques for forming the ROVR will operate in different name-spaces. [RFC6775] operates on EUI-64(TM) addresses. [I-D.ietf-6lo-ap-nd] generates cryptographic tokens. While collisions are not expected in the EUI-64 name-space only, they may happen in the case of [I-D.ietf-6lo-ap-nd] and in a mixed situation. An implementation that understands the name-space MUST consider that ROVRs from different name-spaces are different even if they have the same value. An RFC6775-only 6LR or 6LBR will confuse the name-spaces, which slightly increases the risk of a ROVR collision. A collision of ROVR has no effect if the two Registering Nodes register different addresses, since the ROVR is only significant within the context of one registration. A ROVR is not expected to be unique to one registration, as this specification

allows a node to use the same ROVR to register multiple IPv6 addresses. This is why the ROVR MUST NOT be used as a key to identify the Registering Node, or as an index to the registration. It is only used as a match to ensure that the node that updates a registration for an IPv6 address is the node that made the original registration for that IPv6 address. Also, when the ROVR is not an EUI-64 address, then it MUST NOT be used as the interface ID of the Registered Address. This way, a registration that uses that ROVR will not collide with that of an IPv6 Address derived from EUI-64 and using the EUI-64 as ROVR per [RFC6775].

The Registering Node SHOULD store the ROVR, or enough information to regenerate it, in persistent memory. If this is not done and an event such as a reboot causes a loss of state, re-registering the same address could be impossible until the 6LRs and the 6LBR time out the previous registration, or a management action is taken to clear the relevant state in the network.

5.4. Extended Duplicate Address Messages

In order to map the new EARO content in the Extended Duplicate Address (EDA) messages, a new TID field is added to the Extended DAR (EDAR) and the Extended DAC (EDAC) messages as a replacement of the Reserved field, and a non-null value of the ICMP Code indicates support for this specification. The format of the EDA messages is presented in Section 4.2.

As with the EARO, the Extended Duplicate Address messages are backward compatible with the RFC6775-only versions as long as the ROVR field is 64 bits long. Remarks concerning backwards compatibility for the protocol between the 6LN and the 6LR apply similarly between a 6LR and a 6LBR.

5.5. Registering the Target Address

An NS message with an EARO is a registration if and only if it also carries an SLLA Option [RFC6775]. The EARO is also used in NS and NA messages between Backbone Routers [I-D.ietf-6lo-backbone-router] over the Backbone Link to sort out the distributed registration state; in that case, it does not carry the SLLA Option and is not confused with a registration.

The Registering Node is the node that performs the registration to the 6BBR. As in [RFC6775], it may be the Registered Node as well, in which case it registers one of its own addresses and indicates its own MAC Address as Source Link Layer Address (SLLA) in the NS(EARO).

This specification adds the capability to proxy the registration operation on behalf of a Registered Node that is reachable over an LLN mesh. In that case, if the Registered Node is reachable from the 6BBR over a Mesh-Under mesh, the Registering Node indicates the MAC Address of the Registered Node as the SLLA in the NS(EARO). If the Registered Node is reachable over a Route-Over mesh from the Registering Node, the SLLA in the NS(ARO) is that of the Registering Node. This enables the Registering Node to attract the packets from the 6BBR and route them over the LLN to the Registered Node.

In order to enable the latter operation, this specification changes the behavior of the 6LN and the 6LR so that the Registered Address is found in the Target Address field of the NS and NA messages as opposed to the Source Address field. With this convention, a TLLA option indicates the link-layer address of the 6LN that owns the address.

A Registering Node (e.g., a 6LBR also acting as RPL Root) that advertises reachability for the 6LN MUST place its own Link Layer Address in the SLLA Option of the registration NS(EARO) message. This maintains compatibility with RFC6775-only 6LoWPAN ND [RFC6775].

5.6. Link-Local Addresses and Registration

LLN nodes are often not wired and may move. There is no guarantee that a Link-Local Address remain unique among a huge and potentially variable set of neighboring nodes.

Compared to [RFC6775], this specification only requires that a Link-Local Address be unique from the perspective of the two nodes that use it to communicate (e.g., the 6LN and the 6LR in an NS/NA exchange). This simplifies the DAD process in a Route-Over topology for Link-Local Addresses by avoiding an exchange of EDA messages between the 6LR and a 6LBR for those addresses.

An exchange between two nodes using Link-Local Addresses implies that they are reachable over one hop. A node MUST register a Link-Local Address to a 6LR in order to obtain further reachability by way of that 6LR, and in particular to use the Link-Local Address as source address to register other addresses, e.g., global addresses.

If there is no collision with a previously registered address, then the Link-Local Address is unique from the standpoint of this 6LR and the registration is not a duplicate. Two different 6LRs might claim the same Link-Local Address but different link-layer addresses. In that case, a 6LN MUST only interact with at most one of the 6LRs.

The exchange of EDA messages between the 6LR and a 6LBR, which ensures that an address is unique across the domain covered by the 6LBR, does not need to take place for Link-Local Addresses.

When sending an NS(EARO) to a 6LR, a 6LN MUST use a Link-Local Address as the source address of the registration, whatever the type of IPv6 address that is being registered. That Link-Local Address MUST be either an address that is already registered to the 6LR, or the address that is being registered.

When a 6LN starts up, it typically multicasts a RS and receives one or more unicast RA messages from 6LRs. If the 6LR can process EARO messages, then it places a 6CIO in its RA message with the "E" Flag set as required in Section 6.1.

When a Registering Node does not have an already-registered Address, it MUST register a Link-Local Address, using it as both the Source and the Target Address of an NS(EARO) message. In that case, it is RECOMMENDED to use an address for which DAD is not required (see [RFC6775]), e.g., derived from a globally unique EUI-64 address; using the SLLA Option in the NS is consistent with existing ND specifications such as the "Optimistic Duplicate Address Detection (ODAD) for IPv6" [RFC4429]. The 6LN MAY then use that address to register one or more other addresses.

A 6LR that supports this specification replies with an NA(EARO), setting the appropriate status. Since there is no exchange of EDA messages for Link-Local Addresses, the 6LR may answer immediately to the registration of a Link-Local Address, based solely on its existing state and the Source Link-Layer Option that is placed in the NS(EARO) message as required in [RFC6775].

A node registers its IPv6 Global Unicast Addresses (GUAs) to a 6LR in order to establish global reachability for these addresses via that 6LR. When registering with an updated 6LR, a Registering Node does not use a GUA as Source Address, in contrast to a node that complies to [RFC6775]. For non-Link-Local Addresses, the exchange of EDA messages MUST conform to [RFC6775], but the extended formats described in this specification for the DAR and the DAC are used to relay the extended information in the case of an EARO.

5.7. Maintaining the Registration States

This section discusses protocol actions that involve the Registering Node, the 6LR, and the 6LBR. It must be noted that the portion that deals with a 6LBR only applies to those addresses that are registered to it; as discussed in Section 5.6, this is not the case for Link-Local Addresses. The registration state includes all data that is

stored in the router relative to that registration, in particular, but not limited to, an NCE. 6LBRs and 6BBRs may store additional registration information and use synchronization protocols that are out of scope of this document.

A 6LR cannot accept a new registration when its registration storage space is exhausted. In that situation, the EARO is returned in an NA message with a Status Code of "Neighbor Cache Full" (Table 1), and the Registering Node may attempt to register to another 6LR.

If the registry in the 6LBR is full, then the 6LBR cannot decide whether a registration for a new address is a duplicate. In that case, the 6LBR replies to an EDAR message with an EDAC message that carries a new Status Code indicating "6LBR Registry Saturated" (Table 1). Note: this code is used by 6LBRs instead of "Neighbor Cache Full" when responding to a Duplicate Address message exchange and is passed on to the Registering Node by the 6LR. There is no point for the node to retry this registration via another 6LR, since the problem is network-wide. The node may either abandon that address, de-register other addresses first to make room, or keep the address in TENTATIVE state and retry later.

A node renews an existing registration by sending a new NS(EARO) message for the Registered Address, and the 6LR MUST report the new registration to the 6LBR.

A node that ceases to use an address SHOULD attempt to de-register that address from all the 6LRs to which it has registered the address. This is achieved using an NS(EARO) message with a Registration Lifetime of 0. If this is not done, the associated state will remain in the network till the current Registration Lifetime expires and this may lead to a situation where the 6LR resources become saturated, even if they are correctly planned to start with. The 6LR may then take defensive measures that may prevent this node or some other nodes from owning as many addresses as they request (see Section 7).

A node that moves away from a particular 6LR SHOULD attempt to de-register all of its addresses registered to that 6LR and register to a new 6LR with an incremented TID. When/if the node appears elsewhere, an asynchronous NA(EARO) or EDAC message with a Status Code of "Moved" SHOULD be used to clean up the state in the previous location. As described in [I-D.ietf-6lo-backbone-router], the "Moved" status can be used by a 6BBR in an NA(EARO) message to indicate that the ownership of the proxy state on the Backbone Link was transferred to another 6BBR as the consequence of a movement of the device. If the receiver of the message has registration state corresponding to the related address, it SHOULD propagate the status

down the forwarding path to the Registered node (e.g., reversing an existing RPL [RFC6550] path as prescribed in [I-D.ietf-roll-efficient-npdao]). Whether it could do so or not, the receiver MUST clean up said state.

Upon receiving an NS(EARO) message with a Registration Lifetime of 0 and determining that this EARO is the freshest for a given NCE (see Section 5.2), a 6LR cleans up its NCE. If the address was registered to the 6LBR, then the 6LR MUST report to the 6LBR, through a Duplicate Address exchange with the 6LBR, indicating the null Registration Lifetime and the latest TID that this 6LR is aware of.

Upon receiving the EDAR message, the 6LBR evaluates if this is the most recent TID it has received for that particular registry entry. If so, then the EDAR is answered with an EDAC message bearing a Status of "Success" and the entry is scheduled to be removed. Otherwise, a Status Code of "Moved" is returned instead, and the existing entry is maintained.

When an address is scheduled to be removed, the 6LBR SHOULD keep its NCE in a DELAY state [RFC4861] for a configurable period of time, so as to protect a mobile node that de-registered from one 6LR and did not register yet to a new one, or the new registration did not yet reach the 6LBR due to propagation delays in the network. Once the DELAY time is passed, the 6LBR silently removes its entry.

6. Backward Compatibility

This specification changes the behavior of the peers in a registration flow. To enable backward compatibility, a 6LN that registers to a 6LR that is not known to support this specification MUST behave in a manner that is backward-compatible with [RFC6775]. On the contrary, if the 6LR is found to support this specification, then the 6LN MUST conform to this specification when communicating with that 6LR.

A 6LN that supports this specification MUST always use an EARO as a replacement for an ARO in its registration to a router. This is backward-compatible since the 'T' flag and TID field are reserved in [RFC6775], and are ignored by an RFC6775-only router. A router that supports this specification MUST answer an NS(ARO) and an NS(EARO) with an NA(EARO). A router that does not support this specification will consider the ROVR as an EUI-64 address and treat it the same, which has no consequence if the Registered Addresses are different.

6.1. Signaling EARO Capability Support

"Generic Header Compression for IPv6 over 6LoWPANs" [RFC7400] specifies the 6LoWPAN Capability Indication Option (6CIO) to indicate a node's capabilities to its peers. The 6CIO MUST be present in both Router Solicitation (RS) and Router Advertisement (RA) messages, unless the 6CIO information was already shared in recent exchanges, or pre-configured in all nodes in a network. In any case, a 6CIO MUST be placed in an RA message that is sent in response to an RS with a 6CIO.

Section 4.3 defines a new flag for the 6CIO to signal support for EARO by the issuer of the message. New flags are also added to the 6CIO to signal the sender's capability to act as a 6LR, 6LBR, and 6BBR (see Section 4.3).

Section 4.3 also defines a new flag that indicates the support of EDA messages by the 6LBR. This flag is valid in RA messages but not in RS messages. More information on the 6LBR is found in a separate Authoritative Border Router Option (ABRO). The ABRO is placed in RA messages as prescribed by [RFC6775]; in particular, it MUST be placed in an RA message that is sent in response to an RS with a 6CIO indicating the capability to act as a 6LR, since the RA propagates information between routers.

6.2. RFC6775-only 6LN

An RFC6775-only 6LN will use the Registered Address as the source address of the NS message and will not use an EARO. An updated 6LR MUST accept that registration if it is valid per [RFC6775], and it MUST manage the binding cache accordingly. The updated 6LR MUST then use the RFC6775-only DAR and DAC messages as specified in [RFC6775] to indicate to the 6LBR that the TID is not present in the messages.

The main difference from [RFC6775] is that the exchange of EDA messages for the purpose of DAD is avoided for Link-Local Addresses. In any case, the 6LR MUST use an EARO in the reply, and can use any of the Status codes defined in this specification.

6.3. RFC6775-only 6LR

An updated 6LN discovers the capabilities of the 6LR in the 6CIO in RA messages from that 6LR; if the 6CIO was not present in the RA, then the 6LR is assumed to be a RFC6775-only 6LR.

An updated 6LN MUST use an EARO in the request regardless of the type of 6LR, RFC6775-only or updated, which implies that the 'T' flag is

set. It MUST use a ROVR of 64 bits if the 6LR is an RFC6775-only 6LR.

If an updated 6LN moves from an updated 6LR to an RFC6775-only 6LR, the RFC6775-only 6LR will send an RFC6775-only DAR message, which cannot be compared with an updated one for freshness. Allowing RFC6775-only DAR messages to update a state established by the updated protocol in the 6LBR would be an attack vector and that cannot be the default behavior. But if RFC6775-only and updated 6LRs coexist temporarily in a network, then it makes sense for an administrator to install a policy that allows this, using some method out of scope for this document.

6.4. RFC6775-only 6LBR

With this specification, the Duplicate Address messages are extended to transport the EARO information. Similarly to the NS/NA exchange, an updated 6LBR MUST always use the EDA messages.

Note that an RFC6775-only 6LBR will accept and process an EDAR message as if it were an RFC6775-only DAR, as long as the ROVR is 64 bits long. An updated 6LR discovers the capabilities of the 6LBR in the 6CIO in RA messages from the 6LR; if the 6CIO was not present in any RA, then the 6LBR is assumed to be a RFC6775-only 6LBR.

If the 6LBR is RFC6775-only, the 6LR MUST use only the 64 leftmost bits of the ROVR, and place the result in the EDAR message to maintain compatibility. This way, the support of DAD is preserved.

7. Security Considerations

This specification extends [RFC6775], and the security section of that document also applies to this document. In particular, the link layer SHOULD be sufficiently protected to prevent rogue access.

[RFC6775] does not protect the content of its messages and expects a lower layer encryption to defeat potential attacks. This specification requires the LLN MAC to provide secure unicast to/from the Backbone Router and secure Broadcast or Multicast from the Backbone Router in a way that prevents tampering with or replaying the Neighbor Discovery messages.

This specification recommends using privacy techniques (see Section 8), and protecting against address theft by methods outside the scope of this document. For instance, "Address Protected Neighbor Discovery for Low-power and Lossy Networks" [I-D.ietf-6lo-ap-nd] guarantees the ownership of the Registered Address using a cryptographic ROVR.

The registration mechanism may be used by a rogue node to attack the 6LR or the 6LBR with a Denial-of-Service attack against the registry. It may also happen that the registry of a 6LR or a 6LBR is saturated and cannot take any more registrations, which effectively denies the requesting node the capability to use a new address. In order to alleviate those concerns, Section 5.7 provides a number of recommendations that ensure that a stale registration is removed as soon as possible from the 6LR and 6LBR. In particular, this specification recommends that:

- o A node that ceases to use an address SHOULD attempt to de-register that address from all the 6LRs to which it is registered. See Section 5.2 for the mechanism to avoid replay attacks and avoiding the use of stale registration information.

- o The Registration lifetimes SHOULD be individually configurable for each address or group of addresses. The nodes SHOULD be configured with a Registration Lifetime that reflects their expectation of how long they will use the address with the 6LR to which it is registered. In particular, use cases that involve mobility or rapid address changes SHOULD use lifetimes that are larger yet of a same order as the duration of the expectation of presence.

- o The router (6LR or 6LBR) SHOULD be configurable so as to limit the number of addresses that can be registered by a single node, but as a protective measure only. In any case, a router MUST be able to keep a minimum number of addresses per node. That minimum depends on the type of device and ranges between 3 for a very constrained LLN and 10 for a larger device. A node may be identified by its MAC address, as long as it is not obfuscated by privacy measures. A stronger identification (e.g., by security credentials) is RECOMMENDED. When the maximum is reached, the router SHOULD use a Least-Recently-Used (LRU) algorithm to clean up the addresses, keeping at least one Link-Local Address. The router SHOULD attempt to keep one or more stable addresses if stability can be determined, e.g., because they are used over a much longer time span than other (privacy, shorter-lived) addresses.

- o In order to avoid denial of registration for the lack of resources, administrators should take great care to deploy adequate numbers of 6LRs to cover the needs of the nodes in their range, so as to avoid a situation of starving nodes. It is expected that the 6LBR that serves an LLN is a more capable node than the average 6LR, but in a network condition where it may become saturated, a particular deployment should distribute the 6LBR functionality, for instance by leveraging a high speed

Backbone Link and Backbone Routers to aggregate multiple LLNs into a larger subnet.

The LLN nodes depend on the 6LBR and the 6BBR for their operation. A trust model MUST be put in place to ensure that only authorized devices are acting in these roles so as to avoid threats such as black-holing or bombing attack whereby an impersonated 6LBR would destroy state in the network by using the "Removed" Status code. This trust model could be at a minimum based on a Layer-2 access control, or could provide role validation as well (see Req5.1 in Appendix B.5).

8. Privacy Considerations

As indicated in Section 3, this protocol does not limit the number of IPv6 addresses that each device can form. However, to mitigate denial-of-service attacks, it can be useful as a protective measure to have a limit that is high enough not to interfere with the normal behavior of devices in the network. A host should be able to form and register any address that is topologically correct in the subnet(s) advertised by the 6LR/6LBR.

This specification does not mandate any particular way for forming IPv6 addresses, but it discourages using EUI-64 for forming the Interface ID in the Link-Local Address because this method prevents the usage of "SEcure Neighbor Discovery (SEND)" [RFC3971], "Cryptographically Generated Addresses (CGA)" [RFC3972], and other address privacy techniques.

"Privacy Considerations for IPv6 Adaptation-Layer Mechanisms" [RFC8065] explains why privacy is important and how to form privacy-aware addresses. All implementations and deployments must consider the option of privacy addresses in their own environments.

The IPv6 address of the 6LN in the IPv6 header can be compressed statelessly when the Interface Identifier in the IPv6 address can be derived from the Lower Layer address. When it is not critical to benefit from that compression, e.g., the address can be compressed statefully, or it is rarely used and/or it is used only over one hop, then privacy concerns should be considered. In particular, new implementations should follow the IETF "Recommendation on Stable IPv6 Interface Identifiers" [RFC8064]. [RFC8064] recommends the use of "A Method for Generating Semantically Opaque Interface Identifiers with IPv6 Stateless Address Autoconfiguration (SLAAC)" [RFC7217] for generating Interface Identifiers to be used in SLAAC.

9. IANA Considerations

> Note to RFC Editor, to be removed: please replace "This RFC" throughout this document by the RFC number for this specification once it is allocated.

IANA is requested to make a number of changes under the "Internet Control Message Protocol version 6 (ICMPv6) Parameters" registry, as follows.

9.1. ARO Flags

IANA is requested to create a new subregistry for "ARO Flags" under the "Internet Control Message Protocol version 6 (ICMPv6) [RFC4443] Parameters". This specification defines 8 positions, bit 0 to bit 7, and assigns bit 6 for the 'R' flag and bit 7 for the 'T' flag (see Section 4.1). The policy is "IETF Review" or "IESG Approval" [RFC8126]. The initial content of the registry is as shown in Table 2.

New subregistry for ARO Flags

ARO Status	Description	Document
0..5	Unassigned	
6	'R' Flag	This RFC
7	'T' Flag	This RFC

Table 2: New ARO Flags

9.2. ICMP Codes

IANA is requested to create 2 new subregistries of the ICMPv6 "Code" Fields registry, which itself is a subregistry of the Internet Control Message Protocol version 6 (ICMPv6) Parameters for the ICMP codes. The new subregistries relate to the ICMP type 157, Duplicate Address Request (shown in Table 3), and 158, Duplicate Address Confirmation (shown in Table 4), respectively. For those ICMP types, the ICMP Code field is split in 2 subfields, the "Code Prefix" and the "Code Suffix". The new subregistries relate to the "Code Suffix" portion of the ICMP Code. The range of "Code Suffix" is 0..15 in all cases. The policy is "IETF Review" or "IESG Approval" [RFC8126] for both subregistries. The new subregistries are to be initialized as follows:

New Code Suffixes for ICMP types 157 DAR message

Code Suffix	Meaning	Reference
0	RFC6775 DAR message	RFC 6775
1	EDAR message with 64bits-long ROVR field	This RFC
2	EDAR message with 128bits-long ROVR field	This RFC
3	EDAR message with 192bits-long ROVR field	This RFC
4	EDAR message with 256bits-long ROVR field	This RFC
5...15	Unassigned	

Table 3: New Code Suffixes for the DAR message

New Code Suffixes for ICMP types 158 DAC message

Code Suffix	Meaning	Reference
0	RFC6775 DAC message	RFC 6775
1	EDAC message with 64bits-long ROVR field	This RFC
2	EDAC message with 128bits-long ROVR field	This RFC
3	EDAC message with 192bits-long ROVR field	This RFC
4	EDAC message with 256bits-long ROVR field	This RFC
5...15	Unassigned	

Table 4: New Code Suffixes for the DAC message

9.3. New ARO Status values

IANA is requested to make additions to the Address Registration Option Status Values Registry as follows:

Address Registration Option Status Values Registry

ARO Status	Description	Document
3	Moved	This RFC
4	Removed	This RFC
5	Validation Requested	This RFC
6	Duplicate Source Address	This RFC
7	Invalid Source Address	This RFC
8	Registered Address topologically incorrect	This RFC
9	6LBR Registry saturated	This RFC
10	Validation Failed	This RFC

Table 5: New ARO Status values

9.4. New 6LoWPAN Capability Bits

IANA is requested to make additions to the Subregistry for "6LoWPAN Capability Bits" as follows:

Subregistry for "6LoWPAN Capability Bits" under the "Internet Control Message Protocol version 6 (ICMPv6) Parameters"

Capability Bit	Description	Document
10	EDA Support (D bit)	This RFC
11	6LR capable (L bit)	This RFC
12	6LBR capable (B bit)	This RFC
13	6BBR capable (P bit)	This RFC
14	EARO support (E bit)	This RFC

Table 6: New 6LoWPAN Capability Bits

10. Acknowledgments

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11. References

11.1. Normative References

[RFC2119] Bradner, S., "Key words for use in RFCs to Indicate Requirement Levels", BCP 14, RFC 2119, DOI 10.17487/RFC2119, March 1997, <https://www.rfc-editor.org/info/rfc2119>.

[RFC4291] Hinden, R. and S. Deering, "IP Version 6 Addressing Architecture", RFC 4291, DOI 10.17487/RFC4291, February 2006, <https://www.rfc-editor.org/info/rfc4291>.

[RFC4443] Conta, A., Deering, S., and M. Gupta, Ed., "Internet Control Message Protocol (ICMPv6) for the Internet Protocol Version 6 (IPv6) Specification", STD 89, RFC 4443, DOI 10.17487/RFC4443, March 2006, <https://www.rfc-editor.org/info/rfc4443>.

[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>.

[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>.

[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>.

[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>.

[RFC8126] Cotton, M., Leiba, B., and T. Narten, "Guidelines for Writing an IANA Considerations Section in RFCs", BCP 26, RFC 8126, DOI 10.17487/RFC8126, June 2017, <https://www.rfc-editor.org/info/rfc8126>.

[RFC8174] Leiba, B., "Ambiguity of Uppercase vs Lowercase in RFC 2119 Key Words", BCP 14, RFC 8174, DOI 10.17487/RFC8174, May 2017, <https://www.rfc-editor.org/info/rfc8174>.

11.2. Terminology Related References

[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>.

[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>.

11.3. Informative References

[I-D.chakrabarti-nordmark-6man-efficient-nd]
Chakrabarti, S., Nordmark, E., Thubert, P., and M. Wasserman, "IPv6 Neighbor Discovery Optimizations for Wired and Wireless Networks", draft-chakrabarti-nordmark-6man-efficient-nd-07 (work in progress), February 2015.

[I-D.delcarpio-6lo-wlanah]
Vega, L., Robles, I., and R. Morabito, "IPv6 over 802.11ah", draft-delcarpio-6lo-wlanah-01 (work in progress), October 2015.

[I-D.hou-6lo-plc]
Hou, J., Hong, Y., and X. Tang, "Transmission of IPv6 Packets over PLC Networks", draft-hou-6lo-plc-03 (work in progress), December 2017.

[I-D.ietf-6lo-ap-nd]
Thubert, P., Sarikaya, B., and M. Sethi, "Address Protected Neighbor Discovery for Low-power and Lossy Networks", draft-ietf-6lo-ap-nd-06 (work in progress), February 2018.

[I-D.ietf-6lo-backbone-router]
Thubert, P., "IPv6 Backbone Router", draft-ietf-6lo-backbone-router-06 (work in progress), February 2018.

[I-D.ietf-6lo-nfc]
Choi, Y., Hong, Y., Youn, J., Kim, D., and J. Choi, "Transmission of IPv6 Packets over Near Field Communication", draft-ietf-6lo-nfc-09 (work in progress), January 2018.

[I-D.ietf-6tisch-architecture]
Thubert, P., "An Architecture for IPv6 over the TSCH mode of IEEE 802.15.4", draft-ietf-6tisch-architecture-14 (work in progress), April 2018.

[I-D.ietf-mboned-ieee802-mcast-problems]
Perkins, C., McBride, M., Stanley, D., Kumari, W., and J. Zuniga, "Multicast Considerations over IEEE 802 Wireless Media", draft-ietf-mboned-ieee802-mcast-problems-01 (work in progress), February 2018.

[I-D.ietf-roll-efficient-npdao]
Jadhav, R., Thubert, P., Sahoo, R., and Z. Cao, "Efficient Route Invalidation", draft-ietf-roll-efficient-npdao-03 (work in progress), March 2018.

[I-D.struik-lwip-curve-representations]
Struik, R., "Alternative Elliptic Curve Representations", draft-struik-lwip-curve-representations-00 (work in progress), October 2017.

[I-D.thubert-roll-unaware-leaves]
Thubert, P., "Routing for RPL Leaves", draft-thubert-roll-unaware-leaves-05 (work in progress), May 2018.

[RFC1958] Carpenter, B., Ed., "Architectural Principles of the Internet", RFC 1958, DOI 10.17487/RFC1958, June 1996, <https://www.rfc-editor.org/info/rfc1958>.

[RFC1982] Elz, R. and R. Bush, "Serial Number Arithmetic", RFC 1982, DOI 10.17487/RFC1982, August 1996, <https://www.rfc-editor.org/info/rfc1982>.

[RFC3610] Whiting, D., Housley, R., and N. Ferguson, "Counter with CBC-MAC (CCM)", RFC 3610, DOI 10.17487/RFC3610, September 2003, <https://www.rfc-editor.org/info/rfc3610>.

[RFC3810] Vida, R., Ed. and L. Costa, Ed., "Multicast Listener Discovery Version 2 (MLDv2) for IPv6", RFC 3810, DOI 10.17487/RFC3810, June 2004, <https://www.rfc-editor.org/info/rfc3810>.

[RFC3971] Arkko, J., Ed., Kempf, J., Zill, B., and P. Nikander, "SEcure Neighbor Discovery (SEND)", RFC 3971, DOI 10.17487/RFC3971, March 2005, <https://www.rfc-editor.org/info/rfc3971>.

[RFC3972] Aura, T., "Cryptographically Generated Addresses (CGA)", RFC 3972, DOI 10.17487/RFC3972, March 2005, <https://www.rfc-editor.org/info/rfc3972>.

[RFC4429] Moore, N., "Optimistic Duplicate Address Detection (DAD) for IPv6", RFC 4429, DOI 10.17487/RFC4429, April 2006, <https://www.rfc-editor.org/info/rfc4429>.

[RFC4941] Narten, T., Draves, R., and S. Krishnan, "Privacy Extensions for Stateless Address Autoconfiguration in IPv6", RFC 4941, DOI 10.17487/RFC4941, September 2007, <https://www.rfc-editor.org/info/rfc4941>.

[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>.

[RFC7217] Gont, F., "A Method for Generating Semantically Opaque Interface Identifiers with IPv6 Stateless Address Autoconfiguration (SLAAC)", RFC 7217, DOI 10.17487/RFC7217, April 2014, <https://www.rfc-editor.org/info/rfc7217>.

[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>.

[RFC7934] Colitti, L., Cerf, V., Cheshire, S., and D. Schinazi, "Host Address Availability Recommendations", BCP 204, RFC 7934, DOI 10.17487/RFC7934, July 2016, <https://www.rfc-editor.org/info/rfc7934>.

[RFC8064] Gont, F., Cooper, A., Thaler, D., and W. Liu, "Recommendation on Stable IPv6 Interface Identifiers", RFC 8064, DOI 10.17487/RFC8064, February 2017, <https://www.rfc-editor.org/info/rfc8064>.

[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>.

[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>.

[RFC8279] Wijnands, IJ., Ed., Rosen, E., Ed., Dolganow, A., Przygienda, T., and S. Aldrin, "Multicast Using Bit Index Explicit Replication (BIER)", RFC 8279, DOI 10.17487/RFC8279, November 2017, <https://www.rfc-editor.org/info/rfc8279>.

11.4. External Informative References

[IEEEstd802154] IEEE, "IEEE Standard for Low-Rate Wireless Networks", IEEE Standard 802.15.4, DOI 10.1109/IEEE P802.15.4-REVd/D01, June 2017, <http://ieeexplore.ieee.org/document/7460875/>.

[Perlman83] Perlman, R., "Fault-Tolerant Broadcast of Routing Information", North-Holland Computer Networks 7: 395-405, 1983, <http://www.cs.illinois.edu/~pbg/courses/cs598fa09/readings/p83.pdf>.

Appendix A. Applicability and Requirements Served (Not Normative)

This specification extends 6LoWPAN ND to provide a sequence number to the registration and serves the requirements expressed in Appendix B.1 by enabling the mobility of devices from one LLN to the next based on the complementary work in the "IPv6 Backbone Router" [I-D.ietf-6lo-backbone-router] specification.

"6TiSCH architecture" [I-D.ietf-6tisch-architecture] describes how a 6LoWPAN ND host using the Timeslotted Channel Hopping (TSCH) mode of IEEE Std. 802.15.4 [IEEEstd802154] can connect to the Internet via a RPL mesh network. Doing so requires additions to the 6LoWPAN ND protocol to support mobility and reachability in a secure and manageable network environment. This document specifies those new operations, and fulfills the requirements listed in Appendix B.2.

The term LLN is used loosely in this document, and intended to cover multiple types of WLANs and WPANs, including Low-Power IEEE Std. 802.11 networking, Bluetooth Low Energy, IEEE Std. 802.11ah, and IEEE Std. 802.15.4 wireless meshes, so as to address the requirements discussed in Appendix B.3.

This specification can be used by any wireless node to associate at Layer-3 with a 6BBR and register its IPv6 addresses to obtain routing services including proxy-ND operations over a Backbone Link, effectively providing a solution to the requirements expressed in Appendix B.4.

This specification is extended by "Address Protected Neighbor Discovery for Low-power and Lossy Networks" [I-D.ietf-6lo-ap-nd] to providing a solution to some of the security-related requirements expressed in Appendix B.5.

"Efficiency aware IPv6 Neighbor Discovery Optimizations" [I-D.chakrabarti-nordmark-6man-efficient-nd] suggests that 6LoWPAN ND [RFC6775] can be extended to other types of links beyond IEEE Std. 802.15.4 for which it was defined. The registration technique is beneficial when the Link-Layer technique used to carry IPv6 multicast packets is not sufficiently efficient in terms of delivery ratio or energy consumption in the end devices, in particular to enable energy-constrained sleeping nodes. The value of such extension is especially apparent in the case of mobile wireless nodes, to reduce the multicast operations that are related to IPv6 ND ([RFC4861], [RFC4862]) and affect the operation of the wireless medium [I-D.ietf-mboned-ieee802-mcast-problems]. This serves the scalability requirements listed in Appendix B.6.

Appendix B. Requirements (Not Normative)

This section lists requirements that were discussed by the 6lo WG for an update to 6LoWPAN ND. How those requirements are matched with existing specifications at the time of this writing is shown in Appendix B.8.

B.1. Requirements Related to Mobility

Due to the unstable nature of LLN links, even in an LLN of immobile nodes, a 6LN may change its point of attachment from 6LR-a to 6LR-b, 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, e.g., by using some signaling upon the detection of the movement, or using a keep-alive

mechanism with a period that is consistent with the application needs.

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

Req1.2: For that purpose, the protocol MUST enable differentiating 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 able to register its Address concurrently to multiple 6LRs.

B.2. Requirements Related to Routing Protocols

The point of attachment of a 6LN may be a 6LR in an LLN mesh. IPv6 routing in an LLN can be based on RPL, which is the routing protocol that was defined by the IETF for this particular purpose. Other routing protocols are also considered by Standards Development Organizations (SDO) on the basis of the expected network characteristics. It is required that a 6LN attached via ND to a 6LR indicates whether it participates in the selected routing protocol to obtain reachability via the 6LR, or whether it expects the 6LR to manage its reachability.

The specified updates enable other specifications to define new services such as Source Address Validation (SAVI) with [I-D.ietf-6lo-ap-nd], participation as an unaware leaf to a routing protocol such as the "Routing Protocol for Low Power and Lossy Networks" [RFC6550] (RPL) with [I-D.thubert-roll-unaware-leaves], and registration to a backbone routers performing proxy Neighbor Discovery in a Low-Power and Lossy Network (LLN) with [I-D.ietf-6lo-backbone-router].

Beyond 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 [RFC8279] proposes an optimized technique to enable multicast in an LLN with a very limited requirement for routing state in the nodes.

Related requirements are:

Req2.1: The ND registration method SHOULD be extended so that the 6LR is instructed whether to advertise the Address of a 6LN 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 section 6.4 of [RFC6550], in particular the capability to compute a Path Sequence 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.

B.3. Requirements Related to the Variety of Low-Power Link types

6LoWPAN ND [RFC6775] was defined with a focus on IEEE Std.802.15.4 and in particular the capability to derive a unique identifier from a globally unique EUI-64 address. At this point, the 6lo Working Group is extending the 6LoWPAN Header Compression (HC) [RFC6282] technique to other link types including ITU-T G.9959 [RFC7428], Master-Slave/ Token-Passing [RFC8163], DECT Ultra Low Energy [RFC8105], Near Field Communication [I-D.ietf-6lo-nfc], IEEE Std. 802.11ah [I-D.delcarpio-6lo-wlanah], as well as Bluetooth(R) Low Energy [RFC7668], and Power Line Communication (PLC) [I-D.hou-6lo-plc] Networks.

Related requirements are:

Req3.1: The support of the registration mechanism SHOULD be extended to more LLN links than IEEE Std.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 Neighbor Discovery should specify the formation of a site-local address that follows the security recommendations from [RFC7217].

B.4. Requirements Related to Proxy Operations

Duty-cycled devices may not be able to answer themselves to a lookup from a node that uses IPv6 ND on a Backbone Link 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 SHOULD 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, on the order of multiple days to a month.

B.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 an 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 prevented.

Req5.3: 6LoWPAN ND security mechanisms SHOULD NOT lead to large 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 IEEE Std.802.15.4 [IEEEstd802154] 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 used.

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 the variation of CCM [RFC3610] called 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. Algorithm agility and support for large keys (e.g., 256-bit key sizes) is also desirable, following at Layer-3 the introduction of those capabilities at Layer-2.

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 6LN that registered it

initially, and, if not, determine the rightful owner and deny or clean up the registration that is duplicate.

B.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 to more hops.

B.7. Requirements Related to Operations and Management

Section 3.8 of "Architectural Principles of the Internet" [RFC1958] recommends to: "avoid options and parameters whenever possible. Any options and parameters should be configured or negotiated dynamically rather than manually". This is especially true in LLNs where the number of devices may be large and manual configuration is infeasible. Capabilities for a dynamic configuration of LLN devices can also be constrained by the network and power limitation.

A Network Administrator should be able to validate that the network is operating within capacity, and that in particular a 6LBR does not get overloaded with an excessive amount of registration, so the administrator can take actions such as adding a Backbone Link with additional 6LBRs and 6BBRs to the network.

Related requirements are:

Req7.1: A management model SHOULD be provided that enables access to the 6LBR, monitor its usage vs. capacity, and alert in case of congestion. It is recommended that the 6LBR be reachable over a non-LLN link.

Req7.2: A management model SHOULD be provided that enables access to the 6LR and its capacity to host additional NCE. This management model SHOULD avoid polling individual 6LRs in a way that could disrupt the operation of the LLN.

Req7.3: Information on successful and failed registration SHOULD be provided, including information such as the ROVR of the 6LN, the Registered Address, the address of the 6LR, and the duration of the registration flow.

Req7.4: In case of a failed registration, information on the failure including the identification of the node that rejected the registration and the status in the EARO SHOULD be provided.

B.8. Matching Requirements with Specifications

I-drafts/RFCs addressing requirements

Requirement	Document
Req1.1	[I-D.ietf-6lo-backbone-router]
Req1.2	[RFC6775]
Req1.3	[RFC6775]
Req1.4	This RFC
Req2.1	This RFC
Req2.2	This RFC
Req2.3	
Req3.1	Technology Dependent
Req3.2	Technology Dependent
Req3.3	Technology Dependent
Req3.4	Technology Dependent
Req4.1	This RFC
Req4.2	This RFC
Req4.3	[RFC6775]
Req5.1	
Req5.2	[I-D.ietf-6lo-ap-nd]

Req5.3	
Req5.4	
Req5.5	[I-D.ietf-6lo-ap-nd]
Req5.6	[I-D.struik-lwip-curve-representations]
Req5.7	[I-D.ietf-6lo-ap-nd]
Req5.8	
Req5.9	[I-D.ietf-6lo-ap-nd]
Req6.1	This RFC
Req6.2	This RFC
Req7.1	
Req7.2	
Req7.3	
Req7.4	

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