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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

The scope of this draft is an IPv6 Low Power Network including star and mesh topologies. This specification modifies and extends the behavior and protocol elements of "Neighbor Discovery Optimization for IPv6 over Low-Power Wireless Personal Area Networks" (6LoWPAN ND) [RFC6775] to enable additional capabilities and enhancements including:

- determining the freshest location in case of mobility (TID)
- Simplifying the registration flow for Link-Local Addresses
- Support of a Leaf Node in a Route-Over network
- Proxy registration in a Route-Over network
- Registration to a IPv6 ND proxy over a Backbone Link (6BBR)
- Clarification of support for privacy and temporary addresses

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. Subset of a 6LoWPAN Glossary

This document often uses the following acronyms:

6BBR: 6LoWPAN Backbone Router (proxy for the registration)
6LBR: 6LoWPAN Border Router (authoritative on DAD)
6LN: 6LoWPAN Node
6LR: 6LoWPAN Router (relay to the registration process)

6CIO: Capability Indication Option
(E)ARO: (Extended) Address Registration Option
DAD: Duplicate Address Detection
LLN: Low Power Lossy Network (a typical IoT network)
NA: Neighbor Advertisement
NCE: Neighbor Cache Entry
ND: Neighbor Discovery
NDP: Neighbor Discovery Protocol
NS: Neighbor Solicitation
ROVR: Registration Ownership Verifier
TSCH: TimeSlotted Channel Hopping
TID: Transaction ID (a sequence counter in the EARO)

2.3. References

The Terminology used in this document is consistent with and incorporates that described in Terms Used in Routing for Low-Power and Lossy Networks (LLNs). [RFC7102].

Other terms in use in LLNs are found in Terminology for Constrained-Node Networks [RFC7228].

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],
- "Problem Statement and Requirements for IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) Routing" [RFC6606],
- "IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs): Overview, Assumptions, Problem Statement, and Goals" [RFC4919] and
- "Neighbor Discovery Optimization for Low-power and Lossy Networks" [RFC6775].

2.4. New Terms

This specification introduces the following terminology:

Backbone Link: An IPv6 transit link that interconnects two or more Backbone Routers. It is expected to be of high speed compared to the LLN in order to carry the traffic that is required to federate multiple segments of the potentially large LLN into a single IPv6 subnet.

Backbone Router: A logical network function in an IPv6 router that federates a LLN over a Backbone Link. In order to do so, the Backbone Router (6BBR) proxies the 6LoWPAN ND operations detailed in this document onto the matching operations that run over the backbone, typically IPv6 ND. Note that 6BBR is a

logical function, just like 6LR and 6LBR, and that the same physical router may operate all three.

Extended LLN: Multiple LLNs as defined in [RFC6550], interconnected by a Backbone Link via Backbone Routers, and forming a single IPv6 MultiLink Subnet.

Registration: The process during which a 6LN registers an IPv6 Address with a 6LR in order to obtain services such as DAD and routing back. Duding that flow, the 6LBR may serve as proxy for the registration of the 6LN to the 6BBR so the 6BBR can provide IPv6 ND proxy services over the Backbone.

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

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; this may be the Registered Node, or a proxy such as a 6LBR performing a registration to a 6BBR, on behalf of the Registered Node.

Registered Address: An address owned by the Registered Node that was or is being registered.

RFC6775-only: Applied to a type of node or a type of message, this adjective indicates a behavior that is strictly as specified by [RFC6775] as opposed to updated with this specification.

updated: Qualifies a 6LN, a 6LR or a 6LBR that supports this specification.

3. Applicability of Address Registration Options

The purpose of the Address Registration Option (ARO) in [RFC6775] is to facilitate duplicate address detection (DAD) for hosts as well as to populate 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.

With this specification, a failed or useless registration can be detected 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]; or 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. Rather, the intention is to conform to "Host Address Availability Recommendations" [RFC7934].

In particular, the freedom to form and register addresses is needed for enhanced privacy; each host may register a number of addresses using mechanisms such as "Privacy Extensions for Stateless Address Autoconfiguration (SLAAC) in IPv6" [RFC4941].

In IPv6 ND [RFC4861], a router needs enough storage to hold NCEs for all the addresses to which it can currently forward packets. A router using the Address Registration mechanism also 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.

A network administrator MUST deploy updated 6LR/6LBRs to support the number and type of devices in their network, based on the number of IPv6 addresses that those devices require and their address renewal rate and behavior.

4. Updating RFC 6775

This specification introduces the Extended Address Registration Option (EARO) based on the ARO as defined [RFC6775]. A "T" flag is added to indicate that a new field, the Transaction ID (TID) is populated. The "T" flag MUST be set in NS messages when this specification is used, and echoed in NA messages to confirm that the protocol is supported. The EUI-64 field is overloaded to carry different types of information and its size may be increased when backward compatibility is not an issue.

The extensions to the ARO option are used in the Duplicate Address messages, the Duplicate Address Request (DAR) and Duplicate Address Confirmation (DAC), so as to 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 1. Note that this specification avoids the Duplicate Address message flow for Link-Local Addresses in a Route-Over [RFC6606] topology.

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

Figure 1: (Re-)Registration Flow

In order to support various types of link layers, it is RECOMMENDED to allow multiple registrations, including for privacy / temporary addresses. It is also RECOMMENDED to provide new mechanisms to help clean up stale registration state as soon as possible.

Section 5 of [RFC6775] specifies how a 6LN bootstraps an interface and locates available 6LRs. A Registering Node SHOULD prefer registering to a 6LR that is found to support this specification, as discussed in Section 5, over an RFC6775-only one and MUST operate in a backward compatible fashion when attaching to an RFC6775-only 6LR.

4.1. Extended Address Registration Option (EARO)

The Extended ARO (EARO) replaces 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 6.1. More details on backward compatibility can be found in Section 7.

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

o The address that is being registered with a NS with an EARO is now the Target Address, as opposed to the Source Address as specified in [RFC6775] (see Section 4.5). 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 also limits the use of an address as source address before it is registered and the associated DAD process is complete.

- 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 4.3).
- 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.
- This document specifies a new flag in the EARO, the 'R' flag, used by a 6LN, when registering, to indicate that this 6LN is not a router and that it will not handle its own reachability. If the 'R' flag is set, the registering node expects that the 6LR ensures reachability for the registered address by means of routing or proxying ND. A host MUST set the 'R' flag. When not set, the 'R' flag indicates that the Registering Node is a router, which for instance participates to a Route-Over routing protocol such as the IPv6 Routing Protocol for Low-Power and Lossy Networks [RFC6550] (RPL), and that it will take care of injecting its Address over the routing protocol by itself. A router SHOULD NOT set the 'R' flag; if it does, routes towards the router may be installed on its behalf and may interfere with those it injects.
- The specification introduces a Transaction ID (TID) field in the EARO (see Section 4.2). The TID MUST be provided by a node that supports this specification and a new "T" flag MUST be set to indicate so.
- Finally, this specification introduces new status codes to help diagnose the cause of a registration failure (see Table 1).

4.2. 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 detect the freshness of the registration request and to detect one single registration by multiple 6LoWPAN border routers (e.g., 6LBRs and 6BBRs) supporting the same 6LoWPAN. The TID may also be used by the network to route to the current (freshest known) location of a moving node by spotting the most recent TID.

When a Registered Node is registered with multiple 6BBRs in parallel, the same TID MUST be used. This enables the 6BBRs to determine that the registrations are the same, and distinguish that situation from a movement (see section 4 of [I-D.ietf-6lo-backbone-router] and Section 4.7 below).

4.2.1. Comparing TID values

The TID is a sequence counter and its operation is the exact match of the path sequence specified in RPL, the IPv6 Routing Protocol for Low-Power and Lossy Networks [RFC6550] specification.

In order to keep this document self-contained and yet compatible, the text below is an exact copy from section 7.2. "Sequence Counter Operation" of [RFC6550].

A TID is deemed to be fresher than another when its value is greater per 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 detected 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.

4.3. Registration Ownership Verifier

The ROVR field generalizes the EUI-64 field of the ARO defined in [RFC6775]. It is scoped to a registration and enables recognize and block a tentative to register a duplicate address, which is characterized by a different ROVR in the conflicting registrations It can also be used to protect the ownership of a Registered Address, if the proof-of-ownership of the ROVR can be obtained (more in Section 4.6).

The ROVR is allowed to be of different types, as ong as 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 discussed 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 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 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 collision 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 memory, 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.

4.4. 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 a 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 6.2.

As for 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.

4.5. Registering the Target Address

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 a 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. With this convention, a TLLA option indicates the link-layer address of the 6LN that owns the address.

The Registering Node expects packets for the 6LN. Therefore, it MUST place its own Link Layer Address in the SLLA Option that MUST always be placed in a registration NS(EARO) message. This maintains compatibility with RFC6775-only 6LoWPAN ND [RFC6775].

4.6. Link-Local Addresses and Registration

Considering that LLN nodes are often not wired and may move, there is no guarantee that a Link-Local Address stays unique between a potentially variable and unbounded set of neighboring nodes.

Compared to [RFC6775], this specification only requires that a Link-Local Address is 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.

In more details:

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 reachability from that 6LR beyond the current exchange, 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 an address previously registered to this 6LR by another 6LN, then the Link-Local Address is unique from the standpoint of this 6LR and the registration is not a duplicate. Alternatively, two different 6LRs might expose 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 DAD process between the 6LR and a 6LBR, which is based on an exchange of EDA messages, does not need to take place for Link-Local Addresses.

When registering to a 6LR that conforms to this specification, a node 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 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 a Link-Local Address that is (expected to be) globally unique, e.g., derived from a globally unique EUI-64 address. An EARO in the response NA indicates that the 6LR supports this specification.

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 needs to register its IPv6 Global Unicast IPv6 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.

4.7. 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 4.6, 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 in more complex abstract data structures and use protocols that are out of scope of this document to keep them synchronized when they are distributed.

When its resource available to store registration states are exhausted, a 6LR cannot accept a new registration. In that situation, the EARO is returned in a NA message with a Status Code of "Neighbor Cache Full", and the Registering Node may attempt to register to another 6LR.

If the registry in the 6LBR is saturated, then the 6LBR cannot decide whether a registration for a new address is a duplicate. In that case, the 6LBR replies to a 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 immediately via another 6LR, since the problem is global to the network. 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. In order to refresh the registration state in the 6LBR, the registration MUST be reported 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, a state will remain in the network for its Lifetime.

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 shows up 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. For instance, 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 a 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 or not do so, the receiver MUST clean up the 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 4.2), 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 entry in a DELAY state 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 reach yet the 6LBR due to propagation delays in the network. Once the DELAY time is passed, the 6LBR silently removes its entry.

5. Detecting Enhanced ARO Capability Support

The "Generic Header Compression for IPv6 over 6LoWPANs" [RFC7400] introduces the 6LoWPAN Capability Indication Option (6CIO) to indicate a node's capabilities to its peers. The 6CIO MUST be present in Router Advertisement (RA) messages, unless the capabilities of the 6LR are already known by the 6LN. This can be determined by the 6LR if there is an existing registration in place for the 6LN that is based on EARO. This can also be implicit, or configured in all nodes in a network.

Section 6.3 defines a new flag for the 6CIO to signal support for EARO by the issuer of the message, and Section 7.1 specifies how the flag is to be used. A similar flag indicates the support of EDA messages by the 6LBR - note that other information on the 6LBR is found in a separate Authoritative Border Router Option (ABRO) that MUST also be present in RA messages [RFC6775]. New flags are also

added to signal the router's capability to act as a 6LR, 6LBR and 6BBR (see Section 6.3).

6. Extended ND Options And Messages

This specification does not introduce new options, but it modifies existing ones and updates the associated behaviors as specified in the following subsections.

6.1. Extended Address Registration Option (EARO)

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

The Extended Address Registration Option (EARO) replaces the ARO used within Neighbor Discovery NS and NA messages between a 6LN and its 6LR. Similarly, the EDA messages, EDAR and EDAC, replace the DAR and DAC messages so as to transport the new information between 6LRs and 6LBRs across LLN meshes such as 6TiSCH networks.

An NS message with an EARO is a registration if and only if it also carries an SLLA Option. The EARO 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.

When using the EARO, the address being registered is found in the Target Address field of the NS and NA messages.

The EARO extends the ARO and is indicated by the "T" flag set. The format of the EARO is as follows:

```
 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     |   Reserved    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| Reserved  |R|T|     TID       |     Registration Lifetime     |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+              Registration Ownership Verifier                  +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 2: EARO

Option Fields

Type: 33

Length: 8-bit unsigned integer. The length of the option in units of 8 bytes. It MUST be 2 when operating in backward-compatible mode. It MAY be 3, 4 or 5, denoting a ROVR size of 128, 192 and 256 bits respectively.

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.

Value	Description
0..2	See [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 may be placed in an asynchronous NS(ARO) message, or as the rejection of a proxy registration to a Backbone Router
5	Validation Requested: The Registering Node is challenged for owning the Registered Address or for being an acceptable proxy for the registration. This Status is expected in asynchronous messages from a registrar (6LR, 6LBR, 6BBR) to indicate that the registration state is removed, for instance due to a movement of the device.
6	Duplicate Source Address: The address used as source of the NS(ARO) conflicts with an existing registration.
7	Invalid Source Address: The address used as source of the NS(ARO) is not a Link-Local Address as prescribed by this document.
8	Registered Address topologically incorrect: The address being registered is not usable on this link, e.g., it is not topologically correct

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

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

R: If the 'R' flag is set, the registering node expects that the 6LR ensures reachability for the registered address, e.g. by injecting 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: 1-byte integer; a transaction id that is maintained by the node and incremented with each transaction.

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

Registration Ownership Verifier (ROVR): Enables to correlate multiple registrations for a same IPv6 Address. This 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 and used as proof of ownership of the registration. The scope of a ROVR is one registration and it cannot be used to correlate different registrations.

6.2. Extended Duplicate Address Message Formats

The DAR and DAC messages are defined in section 4.4 of [RFC6775]. Those messages follow a common base format, which enables information from the ARO to be transported over multiple hops.

Those messages are extended to adapt to the new EARO format, as follows:

```
       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      |     Code      |          Checksum             |
      +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
      |    Status     |     TID       |     Registration Lifetime     |
      +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
      |                                                               |
      +          Registration Ownership Verifier                      +
      |                                                               |
      +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
      |                                                               |
      +                                                               +
      |                                                               |
      +                       Registered Address                      +
      |                                                               |
      +                                                               +
      |                                                               |
      +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 3: Duplicate Address Messages Format

Modified Message Fields

Code: The ICMP Code as defined in [RFC4443]. The ICMP Code MUST be set to 1 with this specification. An odd value of the ICMP Code indicates that the TID field is present and obeys this specification.

TID: 1-byte integer; same definition and processing as the TID in the EARO as defined in Section 6.1.

Registration Ownership Verifier (ROVR): The size of the ROVR is computed from the overall size of the IPv6 packet. It MUST be 64bits long when operating in backward-compatible mode. This field has the same definition and processing as the ROVR in the EARO option as defined in Section 6.1.

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

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

This specification introduces the "E" flag to indicate that extended ARO can be used in a registration. A 6LR that supports this specification MUST set the "E" flag.

A similar flag "D" indicates the support of Extended Duplicate Address Messages by the 6LBR; A 6LBR that supports this specification

MUST set the "D" flag. The "D" flag is learned from advertisements by a 6LBR, and is propagated down a graph of 6LRs as a node acting as 6LN registers to a 6LR (which could be the 6LBR), and in turn becomes a 6LR to which other 6LNs will register.

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 and a node MUST set all the flags that are relevant to it.

As an example, a 6LBR sets the "B" and "D" flags. If it acts as a 6LR, then it sets the "L" and "E" flags. If it is collocated with a 6BBR, then it also sets the "P" flag.

```
 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 4: New capability Bits L, B, P, E 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.

7. Backward Compatibility

7.1. Discovering the Capabilities of an ND Peer

A 6LR that supports this specification MUST place a 6CIO in its RA messages. A typical flow when a node starts up is that it sends a multicast RS and receives one or more unicast RA messages. If the 6LR can process Extended ARO, then the "E" Flag is set in the RA.

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 compatible with [RFC6775]. On the

contrary, if the 6LR is known to support this specification, then the 6LN MUST conform this specification.

A 6LN that supports this specification MUST always use an EARO as a replacement to an ARO in its registration to a router. This is harmless 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 and treat it the same, which has no consequence if the Registered Addresses are different.

7.2. RFC6775-only 6LoWPAN Node

an RFC6775-only 6LN will use the Registered Address as source 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 EDA 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.

7.3. RFC6775-only 6LoWPAN Router

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 6LoWPAN Router.

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 6LoWPAN Router.

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 can not be compared with an updated one for freshness. Allowing RFC6775-only DAR messages to replace 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 so, and the capability to install such a policy should be configurable in a 6LBR though it is out of scope for this document.

7.4. RFC6775-only 6LoWPAN Border Router

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 si assumed to be a RFC6775-only 6LoWPAN Border Router.

If the 6LBR is RFC6775-only, and the ROVR in the NS(EARO) was more than 64 bits long, then the 6LR MUST truncate the ROVR to the 64 rightmost bit and place the result in the EDAR message to maintain compatibility. This way, the support of DAD is preserved.

8. Security Considerations

This specification extends [RFC6775], and the security section of that document also applies to this as well. In particular, it is expected that the link layer is sufficiently protected to prevent a rogue access, either by means of physical or IP security on the Backbone Link and link layer cryptography on the LLN.

This specification also expects that the LLN MAC provides 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 RA messages.

This specification recommends using privacy techniques (see Section 9), and protection against address theft such as provided by "Address Protected Neighbor Discovery for Low-power and Lossy Networks" [I-D.ietf-6lo-ap-nd], which 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 4.7 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 4.2 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. A node may be identified by MAC address, but a stringer identification (e.g., by security credentials) is RECOMMENDED. When that 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. Address lifetimes SHOULD be individually configurable.
- 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 a LLN is a more capable node then 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 the right 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).

9. Privacy Considerations

As indicated in Section 3, this protocol does not aim at limiting the number of IPv6 addresses that a device can form and if placed, a limit should be a protective measure only, 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] and "Cryptographically Generated Addresses (CGA)" [RFC3972], and that of 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 deployment must consider the option of privacy addresses in their own environment.

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.

10. IANA Considerations

Note to RFC Editor: please replace "This RFC" throughout this document by the RFC number for this specification once it is attributed.

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

10.1. ARO Flags

IANA is requested to create a new subregistry for "ARO Flags". This specification defines 8 positions, bit 0 to bit 7, and assigns bit 7 for the "T" flag in Section 6.1. 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 under the "Internet Control Message Protocol version 6 (ICMPv6) [RFC4443] Parameters"

ARO Status	Description	Document
0..6	Unassigned	
7	"T" Flag	This RFC

Table 2: new ARO Flags

10.2. ICMP Codes

IANA is requested to create a new entry in the ICMPv6 "Code" Fields subregistry of the Internet Control Message Protocol version 6 (ICMPv6) Parameters for the ICMP codes related to the ICMP type 157 and 158 Duplicate Address Request (shown in Table 3) and Confirmation (shown in Table 4), respectively, as follows:

New entries for ICMP types 157 DAR message

Code	Name	Reference
0	Original DAR message	RFC 6775
1	Extended DAR message	This RFC

Table 3: new ICMPv6 Code Fields

New entries for ICMP types 158 DAC message

Code	Name	Reference
0	Original DAC message	RFC 6775
1	Extended DAC message	This RFC

Table 4: new ICMPv6 Code Fields

10.3. 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

10.4. 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

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12.3. External Informative References

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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.

In the context of the TimeSlotted Channel Hopping (TSCH) mode of IEEE Std. 802.15.4 [IEEEstd802154], the "6TiSCH architecture" [I-D.ietf-6tisch-architecture] introduces how a 6LoWPAN ND host could connect to the Internet via a RPL mesh Network, but this requires additions to the 6LoWPAN ND protocol to support mobility and reachability in a secured and manageable environment. This specification details the new operations that are required to implement the 6TiSCH architecture and serves the requirements listed in Appendix B.2.

The term LLN is used loosely in this specification to cover multiple types of WLANs and WPANs, including Low-Power Wi-Fi, BLUETOOTH(R) 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] [I-D.perkins-intarea-multicast-ieee802]. This serves the scalability requirements listed in Appendix B.6.

Appendix B. Requirements (Not Normative)

This section lists requirements that were discussed at 6lo 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 a LLN of immobile nodes a 6LN 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 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 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 are also considered by Standard Development 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 [RFC8279] 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 so that the 6LR is able to 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 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 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 IEEE1901.2 Narrowband Powerline Communication Networks [I-D.popa-6lo-6loplc-ipv6-over-ieee19012-networks] and BLUETOOTH(R) Low Energy [RFC7668].

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 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.

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 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 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 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 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.

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.

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 and 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 he can take actions such as adding a Backbone Link with additional 6LBRs and 6BBRs to his network.

Related requirements are:

Req7.1: A management model SHOULD be provided providing 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 providing access to the 6LR and its capacity to host additional NCE. This management model SHOULD avoid polling individual 6LRs n 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 Dependant
Req3.2	Technology Dependant
Req3.3	Technology Dependant
Req3.4	Technology Dependant
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	

Table 7: Work Addressing requirements

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