IPv6 Backbone Router
draft-ietf-6lo-backbone-router-13

Abstract

   This document updates RFC 6775 and RFC 8505 in order to enable proxy
   services for IPv6 Neighbor Discovery by Routing Registrars called
   Backbone Routers. Backbone Routers are placed along the wireless
   edge of a Backbone, and federate multiple wireless links to form a
   single MultiLink Subnet.

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   This Internet-Draft is submitted in full conformance with the
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   This Internet-Draft will expire on March 29, 2020.

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1. Introduction

IEEE STD. 802.1 [IEEEstd8021] Ethernet Bridging provides an efficient
and reliable broadcast service for wired networks; applications and
protocols have been built that heavily depend on that feature for
their core operation. Unfortunately, Low-Power Lossy Networks (LLNs)
and local wireless networks generally do not provide the broadcast
capabilities of Ethernet Bridging in an economical fashion.

As a result, protocols designed for bridged networks that rely on multicast and broadcast often exhibit disappointing behaviours when employed unmodified on a local wireless medium (see [I-D.ietf-mboned-ieee802-mcast-problems]).

Wi-Fi [IEEEstd80211] Access Points (APs) deployed in an Extended Service Set (ESS) act as Ethernet Bridges [IEEEstd8021], with the property that the bridging state is established at the time of association. This ensures connectivity to the node (STA) and protects the wireless medium against broadcast-intensive Transparent Bridging reactive Lookups. In other words, the association process is used to register the MAC Address of the STA to the AP. The AP subsequently proxies the bridging operation and does not need to forward the broadcast Lookups over the radio.

Like Transparent Bridging, IPv6 [RFC8200] Neighbor Discovery [RFC4861] [RFC4862] Protocol (IPv6 ND) is a reactive protocol, based on multicast transmissions to locate an on-link correspondent and ensure the uniqueness of an IPv6 address. The mechanism for Duplicate Address Detection (DAD) [RFC4862] was designed for the efficient broadcast operation of Ethernet Bridging. Since broadcast can be unreliable over wireless media, DAD often fails to discover duplications [I-D.yourtchenko-6man-dad-issues]. In practice, IPv6 addresses very rarely conflict because of the entropy of the 64-bit Interface IDs, not because address duplications are detected and resolved.

The IPv6 ND Neighbor Solicitation (NS) [RFC4861] message is used for DAD and address Lookup when a node moves, or wakes up and reconnects to the wireless network. The NS message is targeted to a Solicited-Node Multicast Address (SNMA) [RFC4291] and should in theory only reach a very small group of nodes. But in reality, IPv6 multicast messages are typically broadcast on the wireless medium, and so they are processed by most of the wireless nodes over the subnet (e.g., the ESS fabric) regardless of how few of the nodes are subscribed to the SNMA. As a result, IPv6 ND address Lookups and DADs over a large wireless and/or a LowPower Lossy Network (LLN) can consume enough bandwidth to cause a substantial degradation to the unicast traffic service.

Because IPv6 ND messages sent to the SNMA group are broadcasted at the radio MAC Layer, wireless nodes that do not belong to the SNMA group still have to keep their radio turned on to listen to multicast NS messages, which is a total waste of energy for them. In order to reduce their power consumption, certain battery-operated devices such as IoT sensors and smartphones ignore some of the broadcasts, making IPv6 ND operations even less reliable.

These problems can be alleviated by reducing the IPv6 ND broadcasts over wireless access links. This has been done by splitting the broadcast domains and routes between subnets, or even by assigning a /64 prefix to each wireless node (see [RFC8273]).

Another way is to proxy at the boundary of the wired and wireless domains the Layer-3 protocols that rely on MAC Layer broadcast operations. For instance, IEEE 802.11 [IEEEstd80211] situates proxy-ARP (IPv4) and proxy-ND (IPv6) functions at the Access Points (APs). The 6BBR provides a proxy-ND function and can be extended for proxy-ARP in a continuation specification.

Knowledge of which address to proxy for can be obtained by snooping the IPV6 ND protocol (see [I-D.bi-savi-wlan]), but it has been found to be unreliable. An IPv6 address may not be discovered immediately due to a packet loss, or if a "silent" node is not currently using one of its addresses. A change of state (e.g. due to movement) may be missed or misordered, leading to unreliable connectivity and incomplete knowledge of the state of the network.

This specification defines the 6BBR as a Routing Registrar [RFC8505] that provide proxy services for IPv6 Neighbor Discovery. Backbone Routers federate multiple LLNs over a Backbone Link to form a MultiLink Subnet (MLSN). Backbone Routers placed along the LLN edge of the Backbone handle IPv6 Neighbor Discovery, and forward packets on behalf of registered nodes.

An LLN node (6LN) registers all its IPv6 Addresses using an NS(EARO) as specified in [RFC8505] to the 6BBR. The 6BBR is also a Border Router that performs IPv6 Neighbor Discovery (IPv6 ND) operations on its Backbone interface on behalf of the 6LNs that have registered addresses on its LLN interfaces without the need of a broadcast over the wireless medium. Additional benefits are discussed 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. New Terms

   This document introduces the following terminology:

   Federated

        A subnet that comprises a Backbone and one or more (wireless)
        access links, is said to be federated into one MultiLink
        Subnet. The proxy-ND operation of 6BBRs over the Backbone and
        the access links provides the appearance of a subnet for IPv6
        ND.

   Sleeping Proxy

        A 6BBR acts as a Sleeping Proxy if it answers ND Neighbor
        Solicitations over the Backbone on behalf of a Registered Node.

   Routing Proxy

        A Routing Proxy provides IPv6 ND proxy functions and enables
        the MLSN operation over federated links that may not be
        compatible for bridging. The Routing Proxy advertises its own
        MAC Address as the TLLA in the proxied NAs over the Backbone,
        and routes at the Network Layer between the federated links.

   Bridging Proxy

        A Bridging Proxy provides IPv6 ND proxy functions while
        preserving forwarding continuity at the MAC Layer. The
        Bridging Proxy advertises the MAC Address of the Registering
        Node as the TLLA in the proxied NAs over the Backbone. In that
        case, the MAC Address and the mobility of 6LN is still visible
        across the bridged Backbone, and the 6BR may be configured to
        proxy for Link Local Addresses.

   Binding Table

        The Binding Table is an abstract database that is maintained by
        the 6BBR to store the state associated with its registrations.

   Binding

        A Binding is an abstract state associated to one registration,
        in other words one entry in the Binding Table.

[2.3](). Abbreviations

This document uses the following abbreviations:

6BBR: 6LoWPAN Backbone Router

6LBR: 6LoWPAN Border Router

6LN: 6LoWPAN Node

6LR: 6LoWPAN Router

6CIO: Capability Indication Option

ARO: Address Registration Option

DAC: Duplicate Address Confirmation

DAD: Duplicate Address Detection

DAR: Duplicate Address Request

EDAC: Extended Duplicate Address Confirmation

EDAR: Extended Duplicate Address Request

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

RPL: IPv6 Routing Protocol for LLNs

RA: Router Advertisement

RS: Router Solicitation

   TID: Transaction ID

2.4. References

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

   o "Neighbor Discovery for IP version 6" [RFC4861], "IPv6 Stateless
      Address Autoconfiguration" [RFC4862] and "Optimistic Duplicate
      Address Detection" [RFC4429],

   o "Neighbor Discovery Proxies (proxy-ND)" [RFC4389] and "MultiLink
      Subnet Issues" [RFC4903],

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

   o Neighbor Discovery Optimization for Low-Power and Lossy Networks
      [RFC6775] and "Registration Extensions for 6LoWPAN Neighbor
      Discovery" [RFC8505].

3. Overview

   Figure 1 illustrates backbone link federating a collection of LLNs as
   a single IPv6 Subnet, with a number of 6BBRs providing proxy-ND
   services to their attached LLNs.

```
                   |
               +-----+              +-----+       +-----+
     (default) |     |  (Optional) |     |       |     | IPv6
        Router |     |       6LBR  |     |       |     | Node
               +-----+              +-----+       +-----+
                 | Backbone side       |            |
      ----+-------+----------------+---+------------+----+-----
          |                        |                |
       +------+                 +------+          +------+
       | 6BBR |                 | 6BBR |          | 6BBR |
       |      |                 |      |          |      |
       +------+                 +------+          +------+
          o     Wireless side   o   o  o             o o
       o  o    o  o              o o   o  o  o      o  o  o  o o
      o  o o  o o                o   o  o  o  o      o  o  o o o
      o    o  o  o                 o     o  o         o  o   o
         o    o o                    o    o            o o

         LLN                       LLN                 LLN
```
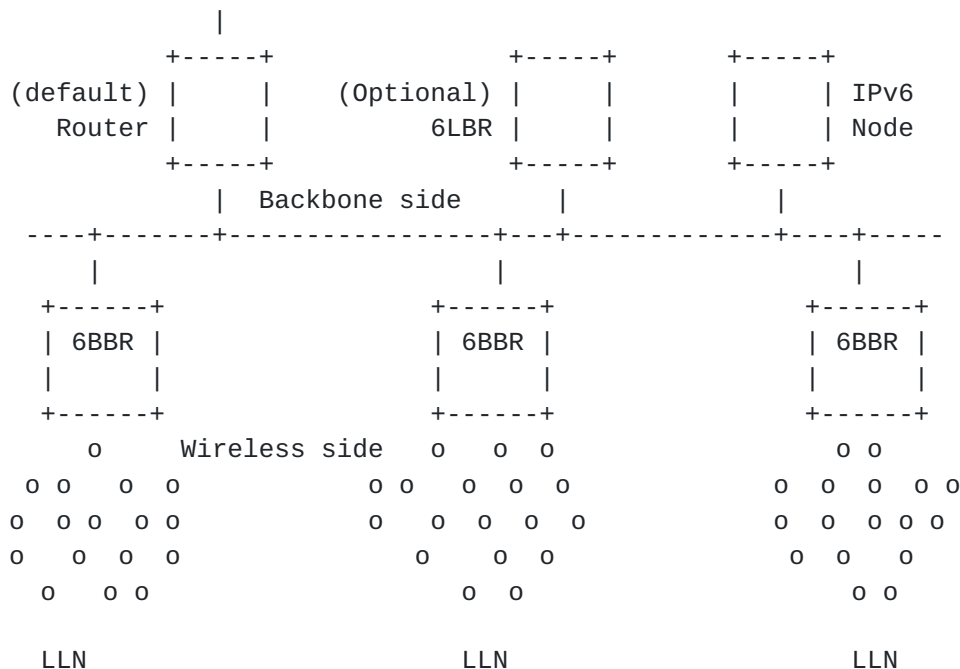
                   Figure 1: Backbone Link and Backbone Routers

The LLN may be a hub-and-spoke access link such as (Low-Power) IEEE
STD. 802.11 (Wi-Fi) [IEEEstd80211] and IEEE STD. 802.15.1 (Bluetooth)
[IEEEstd802151], or a Mesh-Under or a Route-Over network [RFC8505].
The proxy state can be distributed across multiple 6BBRs attached to
the same Backbone.

The main features of a 6BBR are as follows:

o Multilink-subnet functions (provided by the 6BBR on the backbone)
   performed on behalf of registered 6LNs, and

o Routing registrar services that reduce multicast within the LLN:

   * Binding Table management

   * failover, e.g., due to mobility

Each Backbone Router (6BBR) maintains a data structure for its
Registered Nodes called a Binding Table. The combined Binding Tables
of all the 6BBRs on a backbone form a distributed database of 6LNs
that reside in the LLNs or on the IPv6 Backbone.

Unless otherwise configured, a 6BBR does the following:

o Create a new entry in a Binding Table for a new Registered Address
   and ensure that the Address is not duplicated over the Backbone

o Advertise a Registered Address over the Backbone using NA
   messages, asynchronously or as a response to a Neighbor
   Solicitation messages. This includes participating to the
   solicited-node multicast address associated to the Registered
   Address as specified in section 7.2.1. of [RFC4861] over the
   Backbone.

o Either respond using NA messages as a proxy or bridge as a unicast
   frame the IPv6 ND messages (multicast DAD and Address Lookup, and
   unicast NUD) received for the Registered Address over the
   Backbone. This may include responding on behalf of a sleeping
   node, or checking the liveliness of the Registering Node before
   answering on its behalf.

o Deliver packets arriving from the LLN, using Neighbor Solicitation
   messages to look up the destination over the Backbone.

o Forward or bridge packets between the LLN and the Backbone.

o Verify liveness for a registration, when needed.

The first of these functions enables the 6BBR to fulfill its role as
a Routing Registrar for each of its attached LLNs. The remaining
functions fulfill the role of the 6BBRs as the border routers
connecting the Multi-link IPv6 subnet to the Internet.

The proxy-ND operation can co-exist with IPv6 ND over the Backbone.

The 6BBR may co-exist with a proprietary snooping or a traditional
bridging functionality in an Access Point, in order to support legacy
nodes that do not support this specification. In the case, the co-
existing function may turn multicasts into a series of unicast to the
legacy nodes.

The registration to a proxy service uses an NS/NA(EARO) exchange.
The 6BBR operation resembles that of a Mobile IPv6 (MIPv6) [RFC6275]
Home Agent (HA). The combination of a 6BBR and a MIPv6 HA enables
full mobility support for 6LNs, inside and outside the links that
form the subnet.

The 6BBRs use the Extended Address Registration Option (EARO) defined
in [RFC8505] as follows:

o The EARO is used in the IPv6 ND exchanges over the Backbone
   between the 6BBRs to help distinguish duplication from movement.
   Extended Duplicate Address Messages (EDAR and EDAC) MAY also be
   used with a 6LBR, if one is present, and the 6BBR. Address
   duplication is detected using the ROVR field. Conflicting
   registrations to different 6BBRs for the same Registered Address
   are resolved using the TID field.

o The Link Layer Address (LLA) that the 6BBR advertises for the
   Registered Address on behalf of the Registered Node over the
   Backbone can belong to the Registering Node; in that case, the
   6BBR (acting as a Bridging Proxy (see Section 8)) bridges the
   unicast packets. Alternatively, the LLA can be that of the 6BBR
   on the Backbone interface, in which case the 6BBR (acting as a
   Routing Proxy(see Section 7)) receives the unicast packets at
   Layer-3 and routes over.

3.1. Updating RFC 6775 and RFC 8505

This specification adds the EARO as a possible option in RS, NS(DAD)
and NA messages over the backbone. [RFC8505] requires that the
registration NS(EARO) contains an SLLAO. This specification details
the use of those messages over the backbone.

Note: [RFC6775] requires that the registration NS(EARO) contains an
SLLAO and [RFC4862] that the NS(DAD) is sent from the unspecified

address for which there cannot be a SLLAO. Consequently, an NS(DAD)
cannot be confused with a registration.

This specification adds the capability to insert IPv6 ND options in
the EDAR and EDAC messages. In particular, a 6BBR acting as a 6LR
for the Registered Address can insert an SLLAO in the EDAR to the
6LBR in order to avoid a Lookup back. This enables the 6LBR to store
the MAC address associated to the Registered Address on a Link and to
serve as a mapping server as described in
[I-D.thubert-6lo-unicast-lookup].

3.2. Access Link

Figure 2 illustrates a flow where 6LN forms an IPv6 Address and
registers it to a 6BBR acting as a 6LR [RFC8505]. The 6BBRs applies
ODAD (see Section 3.6) to the registered address to enable
connectivity while the message flow is still in progress. In that
example, a 6LBR is deployed on the backbone link to serve the whole
subnet, and EDAR / EDAC messages are used in combination with DAD to
enable coexistence with IPv6 ND over the backbone.

```
        6LN(STA)            6BBR(AP)           6LBR           default GW
           |                   |                 |                 |
           | LLN Access Link   | IPv6 Backbone  (e.g., Ethernet)   |
           |                   |                 |                 |
           |  RS(multicast)    |                 |                 |
           |----------------->|                 |                 |
           | RA(PIO, Unicast) |                 |                 |
           |<-----------------|                 |                 |
           |    NS(EARO)      |                 |                 |
           |----------------->|                 |                 |
           |                   | Extended DAR   |                 |
           |                   |--------------->|                 |
           |                   | Extended DAC   |                 |
           |                   |<---------------|                 |
           |                   |                 |                 |
           |                   |    NS-DAD(EARO, multicast)       |
           |                   |-------->                         |
           |                   |--------------------------------->|
           |                   |                 |                 |
           |                   |    RS(no SLLAO, for ODAD)        |
           |                   |--------------------------------->|
           |                   | if (no fresher Binding) NS(Lookup) |
           |                   |               <---------------|
           |                   |<---------------------------------|
           |                   |    NA(SLLAO, not(O), EARO)       |
           |                   |--------------------------------->|
           |                   |        RA(unicast)              |
           |                   |<---------------------------------|
           |                   |                 |                 |
           |         IPv6 Packets in optimistic mode             |
           |<--------------------------------------------------->|
           |                   |                 |                 |
           |                   |                 |                 |
           |  NA(EARO)        |<DAD timeout>    |                 |
           |<-----------------|                 |                 |
           |                   |                 |                 |
```
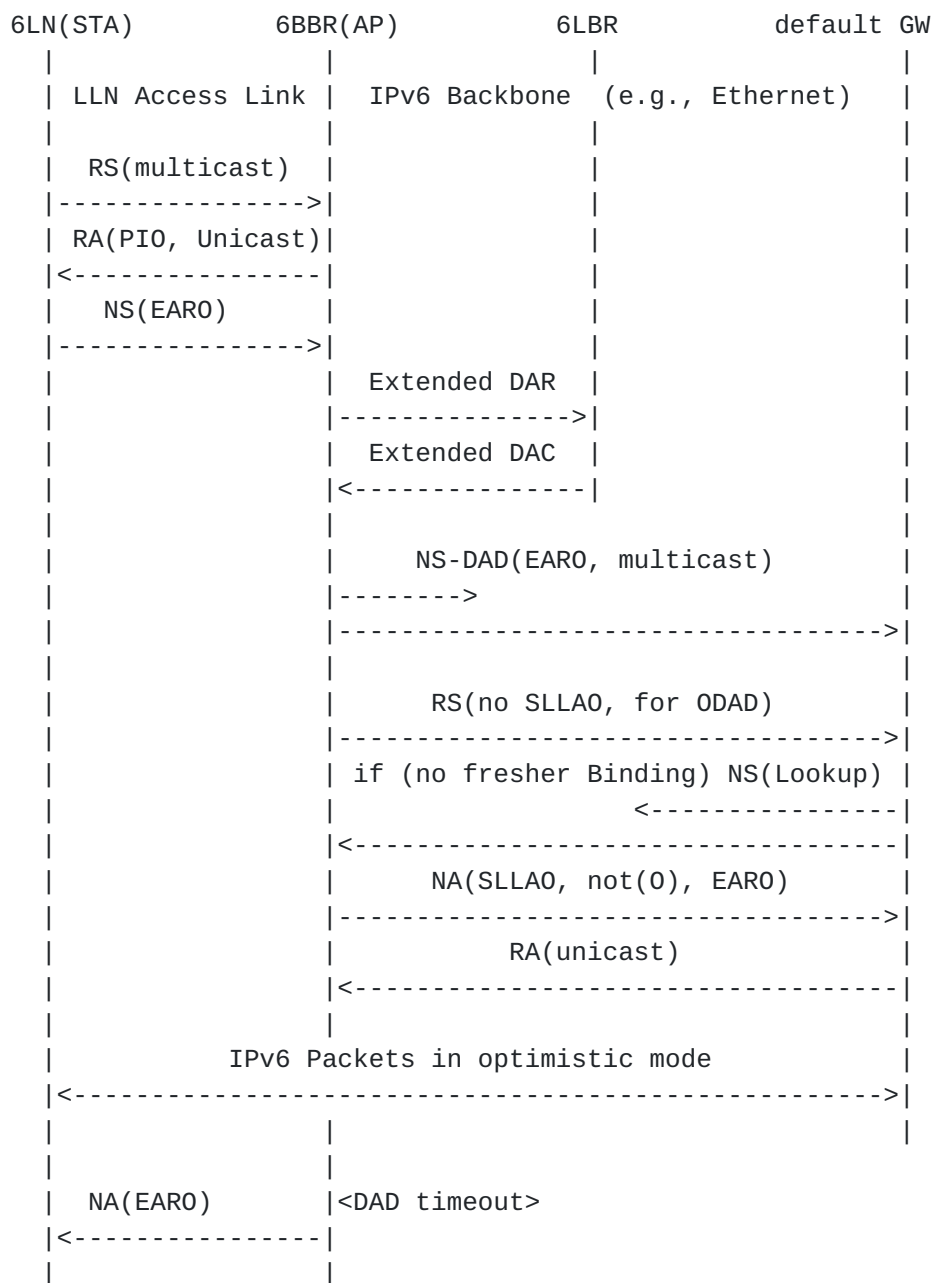
       Figure 2: Initial Registration Flow to a 6BBR acting as Routing Proxy

3.3. Route-Over Mesh

   Figure 3 illustrates IPv6 signaling that enables a 6LN to form a
   Global or a Unique-Local Address and register it to the 6LBR that
   serves its LLN using [RFC8505]. The 6LBR (acting as Registering
   Node) proxies the registration to the 6BBR, using [RFC8505] to
   register the addresses the 6LN (Registered Node) on its behalf to the
   6BBR, and obtain proxy-ND services from the 6BBR.

```
    6LoWPAN Node         6LR              6LBR              6BBR
    (mesh leaf)     (mesh router)    (mesh root)
          |               |                |                 |
          | 6LoWPAN ND    |6LoWPAN ND      | 6LoWPAN ND      | IPv6 ND
          |   LLN link    |Route-Over mesh|Ethernet/serial| Backbone
          |               |                |/Internal call |
          |  IPv6 ND RS   |                |                 |
          |-------------->|                |                 |
          |----------->   |                |                 |
          |------------------->            |                 |
          |  IPv6 ND RA   |                |                 |
          |<-------------|                |                 |
          |               |                |                 |
          |  NS(EARO)     |                |                 |
          |-------------->|                |                 |
          | 6LoWPAN ND    | Extended DAR   |                 |
          |               |-------------->|                 |
          |               |                | NS(EARO)        |
          |               |                |-------------->|
          |               |                | (proxied)     | NS-DAD
          |               |                |               |------>
          |               |                |               | (EARO)
          |               |                |               |
          |               |                | NA(EARO)      |<timeout>
          |               |                |<-------------|
          |               | Extended DAC   |               |
          |               |<-------------|               |
          |  NA(EARO)     |                |               |
          |<-------------|                |               |
          |               |                |               |
```
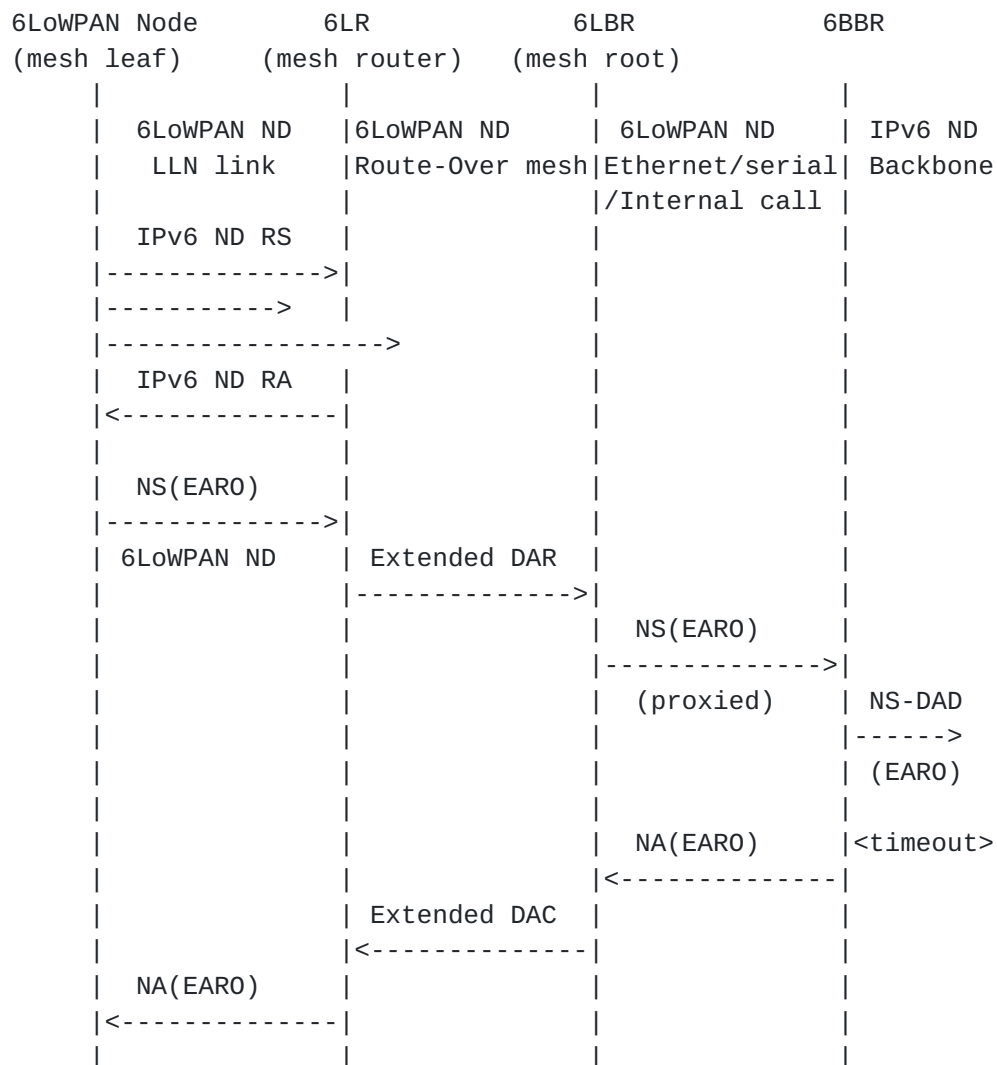
           Figure 3: Initial Registration Flow over Route-Over Mesh

   As a non-normative example of a Route-Over Mesh, the 6TiSCH
   architecture [I-D.ietf-6tisch-architecture] suggests using RPL
   [RFC6550] and collocating the RPL root with a 6LBR that serves the
   LLN, and is either collocated with or connected to the 6BBR over an
   IPv6 Link.

3.4. The Binding Table

   Addresses in a LLN that are reachable from the Backbone by way of the
   6BBR function must be registered to that 6BBR, using an NS(EARO) with
   the R flag set [RFC8505]. A 6BBR maintains a state for its active
   registrations in an abstract Binding Table.

   An entry in the Binding Table is called a "Binding". A Binding may
   be in Tentative, Reachable or Stale state.

The 6BBR uses a combination of [RFC8505] and IPv6 ND over the
Backbone to advertise the registration and avoid a duplication.
Conflicting registrations are solved by the 6BBRs transparently to
the Registering Nodes.

Only one 6LN may register a given Address, but the Address may be
registered to Multiple 6BBRs for higher availability.

Over the LLN, Binding Table management is as follows:

o De-registrations (newer TID, same ROVR, null Lifetime) are
   accepted with a status of 4 ("Removed"); the entry is deleted;

o Newer registrations (newer TID, same ROVR, non-null Lifetime) are
   accepted with a status of 0 (Success); the Binding is updated with
   the new TID, the Registration Lifetime and the Registering Node;
   in Tentative state the EDAC response is held and may be
   overwritten; in other states the Registration Lifetime timer is
   restarted and the entry is placed in Reachable state.

o Identical registrations (same TID, same ROVR) from a same
   Registering Node are accepted with a status of 0 (Success). In
   Tentative state, the response is held and may be overwritten, but
   the response MUST be eventually produced, carrying the result of
   the DAD process;

o Older registrations (older TID, same ROVR) from the same
   Registering Node are discarded;

o Identical and older registrations (not-newer TID, same ROVR) from
   a different Registering Node are rejected with a status of 3
   (Moved); this may be rate limited to avoid undue interference;

o Any registration for the same address but with a different ROVR is
   rejected with a status of 1 (Duplicate).

3.5. Primary and Secondary 6BBRs

A same address may be successfully registered to more than one 6BBR,
in which case the Registering Node uses the same EARO in all the
parallel registrations. To allow for this, ND(DAD) and NA messages
with an EARO that indicate an identical Binding in another 6BBR (same
Registered address, same TID, same ROVR) as silently ignored.

A 6BBR MAY optionally be primary or secondary. The primary is the
6BBR that has the highest EUI-64 Address of all the 6BBRs that share
a registration for the same Registered Address, with the same ROVR
and same Transaction ID, the EUI-64 Address being considered as an

unsigned 64bit integer. A given 6BBR can be primary for a given
Address and secondary for another Address, regardless of whether or
not the Addresses belong to the same 6LN.

In the following sections, is is expected that an NA is sent over the
backbone only if the node is primary or does not support the concept
of primary. More than one 6BBR claiming or defending an address
generates unwanted traffic but no reachability issue since all 6BBRs
provide reachability from the Backbone to the 6LN.

3.6. Using Optimistic DAD

Optimistic Duplicate Address Detection [RFC4429] (ODAD) specifies how
an IPv6 Address can be used before completion of Duplicate Address
Detection (DAD). ODAD guarantees that this behavior will not cause
harm if the new Address is a duplicate.

Support for ODAD avoids delays in installing the Neighbor Cache Entry
(NCE) in the 6BBRs and the default router, enabling immediate
connectivity to the registered node. As shown in Figure 2, if the
6BBR is aware of the Link-Layer Address (LLA) of a router, then the
6BBR sends a Router Solicitation (RS), using the Registered Address
as the IP Source Address, to the known router(s). The RS MUST be
sent without a Source LLA Option (SLLAO), to avoid invalidating a
preexisting NCE in the router.

Following ODAD, the router may then send a unicast RA to the
Registered Address, and it may resolve that Address using an
NS(Lookup) message. In response, the 6BBR sends an NA with an EARO
and the Override (O) flag [RFC4861] that is not set. The router can
then determine the freshest EARO in case of a conflicting NA(EARO)
messages, using the method described in section 5.2.1 of [RFC8505].
If the NA(EARO) is the freshest answer, the default router creates a
Binding with the SLLAO of the 6BBR (in Routing Proxy mode) or that of
the Registering Node (in Bridging Proxy mode) so that traffic from/to
the Registered Address can flow immediately.

4. MultiLink Subnet Considerations

The Backbone and the federated LLN Links are considered as different
links in the MultiLink Subnet, even if multiple LLNs are attached to
the same 6BBR. ND messages are link-scoped and are not forwarded by
the 6BBR between the backbone and the LLNs though some packets may be
reinjected in Bridging Proxy mode (see Section 8).

Nodes located inside the subnet do not perform the IPv6 Path MTU
Discovery [RFC8201]. For that reason, the MTU must have a same value
on the Backbone and all attached LLNs. To achieve this, the 6BBR

MUST use the same MTU value in RAs over the Backbone and in the RAs
that it transmits towards the LLN links.

5. Optional 6LBR serving the MultiLink Subnet

A 6LBR can be deployed to serve the whole MLSN. It may be attached
to the backbone, in which case it can be discovered by its capability
advertisement (see section 4.3. of [RFC8505]) in RA messages.

When a 6LBR is present, the 6BBR uses an EDAR/EDAC message exchange
with the 6LBR to check for duplication or movement. This is done
prior to the NS(DAD) process, which may be avoided of the 6LBR
already maintains a conflicting state for the Registered Address.

This specification enables an address to be registered to more than
one 6BBR. It results that a 6LBR MUST be capable to maintain a state
for each of the 6BBR having registered with a same TID and same ROVR.

If this registration is duplicate or not the freshest, then the 6LBR
replies with an EDAC message with a status code of 1 ("Duplicate
Address") or 3 ("Moved"), respectively. If this registration is the
freshest, then the 6LBR replies with a status code of 0. In that
case, if this registration is fresher than an existing registration
for another 6BBR, then the 6LBR also sends an asynchronous EDAC with
a status of 4 ("Removed") to that other 6BBR.

The EDAR message SHOULD carry the SLLAO used in NS messages by the
6BBR for that Binding, and the EDAC message SHOULD carry the TLLAO
associated with the currently accepted registration. This enables a
6BBR to locate the new position of a mobile 6LN in the case of a
Routing Proxy operation, and opens the capability for the 6LBR to
serve as a mapping server in the future.

Note that if Link Local addresses are registered, then the scope of
uniqueness on which the address duplication is checked is the total
collection of links that the 6LBR serves as opposed to the sole link
on which the Link Local address is assigned.

6. Using IPv6 ND Over the Backbone Link

On the Backbone side, the 6BBR MUST join the SNMA group corresponding
to a Registered Address as soon as it creates a Binding for that
Address, and maintain that SNMA membership as long as it maintains
the registration.

The 6BBR uses either the SNMA or plain unicast to defend the
Registered Addresses in its Binding Table over the Backbone (as
specified in [RFC4862]).

The 6BBR advertises and defends the Registered Addresses over the
Backbone Link using RS, NS(DAD) and NA messages with the Registered
Address as the Source or Target address, respectively.

The 6BBR MUST place an EARO in the IPv6 ND messages that it generates
on behalf of the Registered Node. Note that an NS(DAD) does not
contain an SLLAO and cannot be confused with a proxy registration
such as performed by a 6LBR.

An NA message generated in response to an NS(DAD) MUST have the
Override flag set and a status of 1 (Duplicate) or 3 (Moved) in the
EARO. An NA message generated in response to an NS(Lookup) or an
NS(NUD) MUST NOT have the Override flag set.

This specification enables proxy operation for the IPv6 ND resolution
of LLN devices and a prefix that is used across a MultiLink Subnet
MAY be advertised as on-link over the Backbone. This is done for
backward compatibility with existing IPv6 hosts by setting the L flag
in the Prefix Information Option (PIO) of RA messages [RFC4861].

For movement involving a slow reattachment, the Neighbor
Unreachability Detection (NUD) defined in [RFC4861] may time out too
quickly. Nodes on the backbone SHOULD support [RFC7048] whenever
possible.

7. Routing Proxy Operations

A Routing Proxy provides IPv6 ND proxy functions for Global including
Unique Local addresses between the LLN and the backbone, but not for
Link-Local addresses. It operates as an IPv6 border router and
provides a full Link-Layer isolation.

In this mode, it is not required that the MAC addresses of the 6LNs
are visible at Layer-2 over the Backbone. It is thus useful when the
messaging over the Backbone that is associated to wireless mobility
becomes expensive, e.g., when the Layer-2 topology is virtualized
over a wide area IP underlay.

This mode is definitely required when the LLN uses a MAC address
format that is different from that on the Backbone (e.g., EUI-64 vs.
EUI-48). Since a 6LN may not be able to resolve an arbitrary
destination in the MLSN directly, the MLSN prefix MUST NOT be
advertised as on-link in RA messages sent towards the LLN.

In order to maintain IP connectivity, the 6BBR installs a connected
Host route to the Registered Address on the LLN interface, via the
Registering Node as identified by the Source Address and the SLLA
option in the NS(EARO) messages.

When operating as a Routing Proxy, the 6BBR MUST use its Layer-2
Address on its Backbone Interface in the SLLAO of the RS messages and
the TLLAO of the NA messages that it generates to advertise the
Registered Addresses.

For each Registered Address, multiple peers on the Backbone may have
resolved the Address with the 6BBR MAC Address, maintaining that
mapping in their Neighbor Cache. The 6BBR SHOULD maintain a list of
the peers on the Backbone which have associated its MAC Address with
the Registered Address. If that Registered Address moves to a new
6BBR, the previous 6BBR SHOULD unicast a gratuitous NA with the
Override flag set to each such peer, to supply the LLA of the new
6BBR in the TLLA option for the Address. A 6BBR that does not
maintain this list MAY multicast a gratuitous NA with the Override
flag; this NA will possibly hit all the nodes on the Backbone,
whether or not they maintain an NCE for the Registered Address.

If a correspondent fails to receive the gratuitous NA, it will keep
sending traffic to a 6BBR to which the node was previously
registered. Since the previous 6BBR removed its Host route to the
Registered Address, it will look up the address over the backbone,
resolve the address with the LLA of the new 6BBR, and forward the
packet to the correct 6BBR. The previous 6BBR SHOULD also issue a
redirect message [RFC4861] to update the cache of the correspondent.

8. Bridging Proxy Operations

A Bridging Proxy provides IPv6 ND proxy functions between the LLN and
the backbone while preserving the forwarding continuity at the MAC
Layer. It acts as a Layer-2 Bridge for all types unicast packets
including link-scoped, and appears as an IPv6 Host on the Backbone.

The Bridging Proxy registers any Binding including for a Link-Local
address to the 6LBR (if present) and defends it over the backbone in
IPv6 ND procedures.

To achieve this, the Bridging Proxy intercepts the IPv6 ND messages
and may reinject them on the other side, respond directly or drop
them. For instance, an ND(Lookup) from the backbone that matches a
Binding can be responded directly, or turned into a unicast on the
LLN side to let the 6LN respond.

As a Bridging Proxy, the 6BBR MUST use the Registering Node's Layer-2
Address in the SLLAO of the NS/RS messages and the TLLAO of the NA
messages that it generates to advertise the Registered Addresses.
The Registering Node's Layer-2 address is found in the SLLA of the
registration NS(EARO), and maintained in the Binding Table.

The MultiLink Subnet prefix SHOULD NOT be advertised as on-link in RA
messages sent towards the LLN. If a destination address is seen as
on-link, then a 6LN may use NS(Lookup) messages to resolve that
address. In that case, the 6BBR MUST either answer directly to the
NS(Lookup) message or reinject the message on the backbone, either as
a Layer-2 unicast or a multicast.

If the Registering Node owns the Registered Address, then its
mobility does not impact existing NCEs over the Backbone. Otherwise,
when the 6LN selects another Registering Node, the new Registering
Node SHOULD send a multicast NA with the Override flag set to fix the
existing NCEs across the Backbone. This method can fail if the
multicast message is not received; one or more correspondent nodes on
the Backbone might maintain an stale NCE, and packets to the
Registered Address may be lost. When this condition happens, it is
eventually be discovered and resolved using Neighbor Unreachability
Detection (NUD) as defined in [RFC4861].

9. Creating and Maintaining a Binding

Upon receiving a registration for a new Address (i.e., an NS(EARO)
with the R flag set), the 6BBR creates a Binding and operates as a
6LR according to [RFC8505], interacting with the 6LBR if one is
present.

An implementation of a Routing Proxy that creates a Binding MUST also
create an associated Host route pointing on the registering node in
the LLN interface from which the registration was received.

The 6LR operation is modified as follows:

o EDAR and EDAC messages SHOULD carry a SLLAO and a TLLAO,
   respectively.

o A Bridging Proxy MAY register Link Local addresses to the 6BBR and
   proxy ND for those addresses over the backbone.

o An EDAC message with a status of 9 (6LBR Registry Saturated) is
   assimilated as a status of 0 if a following DAD process protects
   the address against duplication.

This specification enables nodes on a Backbone Link to co-exist along
with nodes implementing IPv6 ND [RFC4861] as well as other non-
normative specifications such as [I-D.bi-savi-wlan]. It is possible
that not all IPv6 addresses on the Backbone are registered and known
to the 6LBR, and an EDAR/EDAC echange with the 6LBR might succeed
even for a duplicate address. Consequently, and unless

administratively overridden, the 6BBR still needs to perform IPv6 ND
DAD over the backbone after an EDAC with a status code of 0 or 9.

For the DAD operation, the Binding is placed in Tentative state for a
duration of TENTATIVE_DURATION, and an NS(DAD) message is sent as a
multicast message over the Backbone to the SNMA associated with the
registered Address [RFC4862]. The EARO from the registration MUST be
placed unchanged in the NS(DAD) message.

If a registration is received for an existing Binding with a non-null
Registration Lifetime and the registration is fresher (same ROVR,
fresher TID), then the Binding is updated, with the new Registration
Lifetime, TID, and possibly Registering Node. In Tentative state
(see Section 9.1), the current DAD operation continues as it was. In
other states (see Section 9.2 and Section 9.3), the Binding is
placed in Reachable state for the Registration Lifetime, and the 6BBR
returns an NA(EARO) to the Registering Node with a status of 0
(Success).

Upon a registration that is identical (same ROVR, TID, and
Registering Node), the 6BBR returns an NA(EARO) back to the
Registering Node with a status of 0 (Success). A registration that
is not as fresh (same ROVR, older TID) is ignored.

If a registration is received for an existing Binding and a
registration Lifetime of zero, then the Binding is removed, and the
6BBR returns an NA(EARO) back to the Registering Node with a status
of 0 (Success). An implementation of a Routing Proxy that removes a
binding MUST remove the associated Host route pointing on the
registering node. It MAY preserve a temporary state in order to
forward packets in flight. The state may be a NCE formed based on a
received NA message, or a Binding in Stale state and pointing at the
new 6BBR on the backbone.

The implementation should also use REDIRECT messages as specified in
[RFC4861] to update the correspondents for the Registered Address,
pointing the new 6BBR.

9.1. Operation on a Binding in Tentative State

The Tentative state covers a DAD period over the backbone during
which an address being registered is checked for duplication using
procedures defined in [RFC4862].

For a Binding in Tentative state:

o The Binding MUST be removed if an NA message is received over the
   Backbone for the Registered Address with no EARO, or containing an

EARO with a status of 1 (Duplicate) that indicates an existing
registration owned by a different Registering Node. In that case,
an NA MUST be sent back to the Registering Node with a status of 1
(Duplicate) in the EARO. This behavior might be overriden by
policy, in particular if the registration is trusted, e.g., based
on the validation of the ROVR field (see [I-D.ietf-6lo-ap-nd]).

o An NS(DAD) with no EARO or with an EARO that indicates a duplicate
   registration (i.e. different ROVR) MUST be answered with an NA
   message containing an EARO with a status of 1 (Duplicate) and the
   Override flag not set. This behavior might be overriden by
   policy, in particular if the registration is not trusted.

o The Binding MUST be removed if an NA message is received over the
   Backbone for the Registered Address containing an EARO with a
   status of 3 (Moved), or an NS(DAD) with an EARO that indicates a
   fresher registration ([RFC8505]) for the same Registered Node
   (i.e. same ROVR). A status of 3 is returned in the NA(EARO) back
   to the Registering Node.

o NS(DAD) and NA messages containing an EARO that indicates a
   registration for the same Registered Node that is not as fresh as
   this SHOULD be answered with an NA message containing an EARO with
   a status of 3 (Moved) in order to clean up the situation
   immediately.

o Other NS(DAD) and NA messages from the Backbone are ignored.

o NS(Lookup) and NS(NUD) messages SHOULD be optimistically answered
   with an NA message containing an EARO with a status of 0 and the
   Override flag not set (see Section 3.6). If optimistic DAD is
   disabled, then they SHOULD be queued to be answered when the
   Binding goes to Reachable state.

When the TENTATIVE_DURATION timer elapses, the Binding is placed in
Reachable state for the Registration Lifetime, and the 6BBR returns
an NA(EARO) to the Registering Node with a status of 0 (Success).

The 6BBR also attempts to take over any existing Binding from other
6BBRs and to update existing NCEs in backbone nodes. This is done by
sending an NA message with an EARO and the Override flag set over the
backbone (see Section 7 and Section 8).

9.2. Operation on a Binding in Reachable State

The Reachable state covers an active registration after a successful
DAD process.

An NS(DAD) with no EARO or with an EARO that indicates a duplicate If
the Registration Lifetime is of a long duration, an implementation
might be configured to reassess the availability of the Registering
Node at a lower period, using a NUD procedure as specified in
[RFC7048]. If the NUD procedure fails, the Binding SHOULD be placed
in Stale state immediately.

For a Binding in Reachable state:

o The Binding MUST be removed if an NA or an NS(DAD) message is
   received over the Backbone for the Registered Address containing
   an EARO that indicates a fresher registration ([RFC8505]) for the
   same Registered Node (i.e. same ROVR). A status of 4 (Removed) is
   returned in an asynchronous NA(EARO) to the Registering Node.
   Based on configuration, an implementation may delay this operation
   by a small timer in order to a allow for a parallel registration
   to arrive to this node, in which case the NA might be ignored.

o An NS(DAD) with no EARO or with an EARO that indicates a duplicate
   registration (i.e. different ROVR) MUST be answered with an NA
   message containing an EARO with a status of 1 (Duplicate) and the
   Override flag not set.

o NS(DAD) and NA messages containing an EARO that indicates a
   registration for the same Registered Node that is not as fresh as
   this MUST be answered with an NA message containing an EARO with a
   status of 3 (Moved).

o Other NS(DAD) and NA messages from the Backbone are ignored.

o NS(Lookup) and NS(NUD) messages SHOULD be answered with an NA
   message containing an EARO with a status of 0 and the Override
   flag not set. The 6BBR MAY check whether the Registering Node is
   still available using a NUD procedure over the LLN prior to
   answering; this behaviour depends on the use case and is subject
   to configuration.

When the Registration Lifetime timer elapses, the Binding is placed
in Stale state for a duration of STALE_DURATION.

9.3. Operation on a Binding in Stale State

The Stale state enables tracking of the Backbone peers that have a
NCE pointing to this 6BBR in case the Registered Address shows up
later.

If the Registered Address is claimed by another 6LN on the Backbone,
with an NS(DAD) or an NA, the 6BBR does not defend the Address.

For a Binding in Stale state:

o The Binding MUST be removed if an NA or an NS(DAD) message is
   received over the Backbone for the Registered Address containing
   no EARO or an EARO that indicates either a fresher registration
   for the same Registered Node or a duplicate registration. A
   status of 4 (Removed) MAY be returned in an asynchronous NA(EARO)
   to the Registering Node.

o NS(DAD) and NA messages containing an EARO that indicates a
   registration for the same Registered Node that is not as fresh as
   this MUST be answered with an NA message containing an EARO with a
   status of 3 (Moved).

o If the 6BBR receives an NS(Lookup) or an NS(NUD) message for the
   Registered Address, the 6BBR MUST attempts a NUD procedure as
   specified in [RFC7048] to the Registering Node, targeting the
   Registered Address, prior to answering. If the NUD procedure
   succeeds, the operation in Reachable state applies. If the NUD
   fails, the 6BBR refrains from answering.

o Other NS(DAD) and NA messages from the Backbone are ignored.

   When the STALE_DURATION timer elapses, the Binding MUST be removed.

10. Registering Node Considerations

   A Registering Node MUST implement [RFC8505] in order to interact with
   a 6BBR (which acts as a routing registrar). Following [RFC8505], the
   Registering Node signals that it requires IPv6 proxy-ND services from
   a 6BBR by registering the corresponding IPv6 Address using an
   NS(EARO) message with the R flag set.

   The Registering Node may be the 6LN owning the IPv6 Address, or a
   6LBR that performs the registration on its behalf in a Route-Over
   mesh.

   The Registering Node SHOULD register all of its IPv6 Addresses to its
   6LR, which is the 6BBR when they are connected at Layer-2. Failure
   to register an address may result in the address being unreachable by
   other parties if the 6BBR cancels the NS(Lookup) over the LLN or to
   selected LLN nodes that are known to register their addresses.

   The Registering Node MUST refrain from using multicast NS(Lookup)
   when the destination is not known as on-link, e.g., if the prefix is
   advertised in a PIO with the L flag that is not set. In that case,
   the Registering Node sends its packets directly to its 6LR.

The Registering Node SHOULD also follow [RFC7772] in order to limit
the use of multicast RAs. It SHOULD also implement Simple Procedures
for Detecting Network Attachment in IPv6 [RFC6059] (DNA procedures)
to detect movements, and support Packet-Loss Resiliency for Router
Solicitations [RFC7559] in order to improve reliability for the
unicast RS messages.

11. Security Considerations

This specification applies to LLNs in which the link layer is
protected, either by means of physical or IP security for the
Backbone Link or MAC-layer security. In particular, the LLN MAC is
required to provide secure unicast to/from the Backbone Router and
secure Broadcast from the Backbone Router in a way that prevents
tampering with or replaying the RA messages.

A possible attack over the backbone can be done by sending an NS with
an EARO and expecting the NA(EARO) back to contain the TID and ROVR
fields of the existing state. With that information, the attacker
can easily increase the TID and take over the Binding.
[I-D.ietf-6lo-ap-nd] guarantees the ownership of a registered address
based on a proof-of-ownership encoded in the ROVR field and protects
against address theft and impersonation.

12. Protocol Constants

This Specification uses the following constants:

TENTATIVE_DURATION: 800 milliseconds

STALE_DURATION: see below

In LLNs with long-lived Addresses such as LPWANs, STALE_DURATION
SHOULD be configured with a relatively long value, by default 24
hours. In LLNs where addresses are renewed rapidly, e.g. for privacy
reasons, STALE_DURATION SHOULD be configured with a relatively long
value, by default 5 minutes.

13. IANA Considerations

This document has no request to IANA.

14. Acknowledgments

Many thanks to Dorothy Stanley, Thomas Watteyne and Jerome Henry for
their various contributions.

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Appendix A. Possible Future Extensions

   With the current specification, the 6LBR is not leveraged to avoid
   multicast NS(Lookup) on the Backbone. This could be done by adding a
   lookup procedure in the EDAR/EDAC exchange.

   By default the specification does not have a trust model, e.g.,
   whereby nodes that associate their address with a proof-of-ownership
   [I-D.ietf-6lo-ap-nd] should be more trusted than nodes that do not.
   Such a trust model and related signaling could be added in the future
   to override the default operation and favor trusted nodes.

   Future documents may extend this specification by allowing the 6BBR
   to redistribute Host routes in routing protocols that would operate
   over the Backbone, or in MIPv6, or FMIP, or the Locator/ID Separation
   Protocol (LISP) [RFC6830] to support mobility on behalf of the 6LNs,
   etc... LISP may also be used to provide an equivalent to the EDAR/
   EDAC exchange using a Map Server / Map Resolver as a replacement to
   the 6LBR.

Appendix B. Applicability and Requirements Served

   This document specifies proxy-ND functions that can be used to
   federate an IPv6 Backbone Link and multiple IPv6 LLNs into a single
   MultiLink Subnet. The proxy-ND functions enable IPv6 ND services for
   Duplicate Address Detection (DAD) and Address Lookup that do not
   require broadcasts over the LLNs.

   The term LLN is used 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, meeting the
   requirements listed in Appendix B.3 of [RFC8505] "Requirements
   Related to Various Low-Power Link Types".

   Each LLN in the subnet is attached at an IPv6 Backbone Router (6BBR).
   The Backbone Routers interconnect the LLNs and advertise the
   Addresses of the 6LNs over the Backbone Link using proxy-ND
   operations.

   This specification updates IPv6 ND over the Backbone to distinguish
   Address movement from duplication and eliminate stale state in the
   Backbone routers and Backbone nodes once a 6LN has roamed. In this
   way, mobile nodes may roam rapidly from one 6BBR to the next and
   requirements in Appendix B.1 of [RFC8505] "Requirements Related to
   Mobility" are met.

   A 6LN can register its IPv6 Addresses and thereby obtain proxy-ND
   services over the Backbone, meeting the requirements expressed in

Appendix B.4 of [RFC8505], "Requirements Related to Proxy
Operations".

The IPv6 ND operation is minimized as the number of 6LNs grows in the
LLN. This meets the requirements in Appendix B.6 of [RFC8505]
"Requirements Related to Scalability", as long has the 6BBRs are
dimensioned for the number of registrations that each needs to
support.

In the case of a Wi-Fi access link, a 6BBR may be collocated with the
Access Point (AP), or with a Fabric Edge (FE) or a CAPWAP [RFC5415]
Wireless LAN Controller (WLC). In those cases, the wireless client
(STA) is the 6LN that makes use of [RFC8505] to register its IPv6
Address(es) to the 6BBR acting as Routing Registrar. The 6LBR can be
centralized and either connected to the Backbone Link or reachable
over IP. The 6BBR proxy-ND operations eliminate the need for
wireless nodes to respond synchronously when a Lookup is performed
for their IPv6 Addresses. This provides the function of a Sleep
Proxy for ND [I-D.nordmark-6man-dad-approaches].

For the TimeSlotted Channel Hopping (TSCH) mode of [IEEEstd802154],
the 6TiSCH architecture [I-D.ietf-6tisch-architecture] describes how
a 6LoWPAN ND host could connect to the Internet via a RPL mesh
Network, but doing so requires extensions to the 6LOWPAN ND protocol
to support mobility and reachability in a secure and manageable
environment. The extensions detailed in this document also work for
the 6TiSCH architecture, serving the requirements listed in
Appendix B.2 of [RFC8505] "Requirements Related to Routing
Protocols".

The registration mechanism may be seen as a more reliable alternate
to snooping [I-D.bi-savi-wlan]. It can be noted that registration
and snooping are not mutually exclusive. Snooping may be used in
conjunction with the registration for nodes that do not register
their IPv6 Addresses. The 6BBR assumes that if a node registers at
least one IPv6 Address to it, then the node registers all of its
Addresses to the 6BBR. With this assumption, the 6BBR can possibly
cancel all undesirable multicast NS messages that would otherwise
have been delivered to that node.

Scalability of the MultiLink Subnet [RFC4903] requires avoidance of
multicast/broadcast operations as much as possible even on the
Backbone [I-D.ietf-mboned-ieee802-mcast-problems]. Although hosts
can connect to the Backbone using IPv6 ND operations, multicast RAs
can be saved by using [I-D.ietf-6man-rs-refresh], which also requires
the support of [RFC7559].

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