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Author: P. Thubert, Ed.

RFC 9685
Listener Subscription for IPv6 Neighbor Discovery Multicast and Anycast Addresses

Abstract

This document updates the 6LoWPAN extensions to IPv6 Neighbor Discovery (specified in RFCs 4861 and 8505) to enable a listener to subscribe to an IPv6 anycast or multicast address. This document also updates the Routing Protocol for Low-Power and Lossy Networks (RPL) (specified in RFCs 6550 and 6553) to add a new Non-Storing multicast mode and new support for anycast addresses in Storing and Non-Storing modes. This document extends RFC 9010 to enable a 6LoWPAN Router (6LR) to inject the anycast and multicast addresses in RPL.

Status of This Memo

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1. Introduction

The design of Low-Power and Lossy Networks (LLNs) is generally focused on saving energy, which is the most constrained resource of all. Other design constraints, such as a limited memory capacity, duty cycling of the LLN devices, and low-power lossy transmissions, derive from that primary concern. The radio (when both transmitting or simply listening) is a major energy drain, and the LLN protocols must be adapted to allow the nodes to remain sleeping with the radio turned off at most times.

"RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks" [RFC6550] provides IPv6 [RFC8200] routing services within such constraints. To save signaling and routing state in constrained networks, the RPL routing is only performed along a Destination-Oriented Directed Acyclic Graph (DODAG) that is optimized to reach a Root node, as opposed to along the shortest path between two peers, which may be a fuzzy concept anyway in a radio LLN.

This stretches the routes between RPL nodes inside the DODAG for a vastly reduced amount of control traffic and routing state that would be required to operate an any-to-any shortest path protocol. Additionally, broken routes may be fixed lazily and on-demand based on data plane inconsistency discovery, which avoids wasting energy in the proactive repair of unused paths.

RPL uses Destination Advertisement Object (DAO) messages to establish Downward routes. DAO messages are an optional feature for applications that require point-to-multipoint (P2MP) or point-to- point (P2P) traffic. RPL supports two modes of Downward traffic: Storing (fully stateful) or Non-Storing (fully source routed); see Section 9 of [RFC6550]. The mode is signaled in the Mode of Operation (MOP) field in the DODAG Information Object (DIO) messages and applies to the whole RPL Instance.

Any given RPL Instance is either Storing or Non-Storing. In both cases, P2P packets travel Up toward a DODAG root then Down to the final destination (unless the destination is on the Upward route). In the Non-Storing case, the packet will travel all the way to a DODAG root before traveling Down. In the Storing case, the packet may be directed Down towards the destination by a common ancestor of the source and the destination prior to reaching a DODAG root. Section 12 of [RFC6550] details the Storing Mode of Operation with multicast support with source-independent multicast routing in RPL.

The classical Neighbor Discovery (ND) protocol [RFC4861] [RFC4862] was defined for serial links and shared transit media such as Ethernet at a time when broadcast on those media types was cheap, while memory for neighbor cache was expensive. It was thus designed as a reactive protocol that relies on caching and multicast operations for the Address Discovery (aka lookup) and Duplicate Address Detection (DAD) of IPv6 unicast addresses. Those multicast operations typically impact every node on-link when at most one is really targeted. This is a waste of energy and implies that all nodes are awake to hear the request, which is inconsistent with power-saving (sleeping) modes.

The original specification for 6LoWPAN ND, "Neighbor Discovery Optimization for IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs)" [RFC6775], was introduced to avoid the excessive use of multicast messages and enable IPv6 ND for operations over energy-constrained nodes. [RFC6775] changes the classical IPv6 ND model to proactively establish the Neighbor Cache Entry (NCE) associated to the unicast address of a 6LoWPAN Node (6LN) in one or more 6LoWPAN Routers (6LRs) that serve it. To that effect, [RFC6775] defines a new Address Registration Option (ARO) that is placed in unicast Neighbor Solicitation (NS) and Neighbor Advertisement (NA) messages between the 6LN and the 6LR.

"Registration Extensions for IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) Neighbor Discovery" [RFC8505] updates [RFC6775] so that a generic Address Registration mechanism can be used to access services such as routing and ND proxy and introduces the Extended Address Registration Option (EARO) for that purpose. This provides a routing-agnostic interface for a host to request that the router injects a unicast IPv6 address in the local routing protocol and provides return reachability for that address.

"Routing for RPL (Routing Protocol for Low-Power and Lossy Networks) Leaves" [RFC9010] provides the router counterpart of the mechanism for a host that implements [RFC8505] to inject its unicast Unique Local Addresses (ULAs) and Global Unicast Addresses (GUAs) in RPL. Although RPL also provides multicast routing, 6LoWPAN ND supports only the registration of unicast addresses, and there is no equivalent of [RFC9010] to specify the 6LR behavior upon the subscription of one or more multicast addresses.

"Multicast Listener Discovery Version 2 (MLDv2) for IPv6" [RFC3810] enables the router to learn which node listens to which multicast address, but as the classical IPv6 ND protocol, MLD relies on multicasting queries to all nodes, which is unfit for low-power operations. As for IPv6 ND, it makes sense to let the 6LNs control when and how they maintain the state associated to their multicast addresses in the 6LR, e.g., during their own wake time. In the case of a constrained node that already implements [RFC8505] for unicast reachability, it makes sense to extend that support to subscribe the multicast addresses they listen to.

This specification Extends [RFC8505] and [RFC9010] by adding the capability for the 6LN to subscribe anycast and multicast addresses and for the 6LR to inject them in RPL when appropriate. Note that due to the unreliable propagation of packets in the LLN, it cannot be guaranteed that any given packet is delivered once and only once. If a breakage happens along the preferred parent tree that is normally used for multicast forwarding, the packet going Up may be rerouted to an alternate parent, leading to potential failures and duplications, whereas a packet going Down will not be delivered in the subtree. It is up to the Upper Layer Protocols (ULPs) to cope with both situations.

2. Terminology

2.1. Requirements Language

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.

In addition, "Extends" and "Amends" are used as more specific terms for "Updates" per Section 3 of [UPDATES-TAG] as follows:

Amends/Amended by: This tag pair is used with an amending RFC that changes the amended RFC. This could include bug fixes, behavior changes, etc. This is intended to specify mandatory changes to the protocol. The goal of this tag pair is to signal to anyone looking to implement the amended RFC that they **MUST** also implement the amending RFC.

Extends/Extended by: This tag pair is used with an extending RFC that defines an optional addition to the extended RFC. This can be used by documents that use existing extension points or clarifications that do not change existing protocol behavior. This signals to implementers and protocol designers that there are changes to the extended RFC that they need to consider but not necessarily implement.

2.2. Terminology from Relevant RFCs

This document uses terms and concepts that are discussed in:

- "Neighbor Discovery for IP version 6 (IPv6)" [RFC4861],
- "IPv6 Stateless Address Autoconfiguration" [RFC4862],

- "RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks" [RFC6550],
- "Neighbor Discovery Optimization for IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs)" [RFC6775],
- "Registration Extensions for IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) Neighbor Discovery" [RFC8505], and
- "Using RPI Option Type, Routing Header for Source Routes, and IPv6-in-IPv6 Encapsulation in the RPL Data Plane" [RFC9008].

2.3. Abbreviations

This document uses the following abbreviations:

6CIO: Capability Indication Option

6LBR: 6LoWPAN Border Router

6LN: 6LoWPAN Node

6LR: 6LoWPAN Router

ARO: Address Registration Option

DAC: Duplicate Address Confirmation

DAD: Duplicate Address Detection

DAO: Destination Advertisement Object

DAR: Duplicate Address Request

DIO: DODAG Information Object

DMB: Direct MAC Broadcast

DODAG: Destination-Oriented Directed Acyclic Graph

EARO: Extended Address Registration Option

EDAC: Extended Duplicate Address Confirmation

EDAR: Extended Duplicate Address Request

IR: Ingress Replication

LLN: Low-Power and Lossy Network

MLD: Multicast Listener Discovery

MOP: Mode of Operation

NA: Neighbor Advertisement

NCE: Neighbor Cache Entry

ND: Neighbor Discovery

NS: Neighbor Solicitation

RA: Router Advertisement

RAN: RPL-Aware Node

ROVR: Registration Ownership Verifier (pronounced "rover")

RPL: Routing Protocol for Low-Power and Lossy Networks (pronounced "ripple")

RS: Router Solicitation

RTO: RPL Target Option

RUL: RPL-Unaware Leaf

TID: Transaction ID

TIO: Transit Information Option

2.4. New Terms

This document introduces the following terms:

Origin: The node that issued an anycast or multicast advertisement, in the form of either an NS(EARO) or a DAO(TIO, RTO) message.

Merge/merging: The action of receiving multiple anycast or multicast advertisements, either internally from self, in the form of an NS(EARO) message, or as a DAO(TIO, RTO) message, and generating a single DAO(TIO, RTO). The RPL router maintains a state per origin for each advertised address and merges the advertisements for all subscriptions for the same address in a single advertisement. A RPL router that merges multicast advertisements from different origins becomes the origin of the merged advertisement and uses its own values for the Path Sequence and Registration Ownership Verifier (ROVR) fields.

Subscribe/subscription: The special form of registration that leverages NS(EARO) to register (or subscribe to) a multicast or an anycast address.

3. Overview

This specification Extends [RFC8505] to provide a registration method (called "subscription" in this case) for anycast and multicast addresses. The specification inherits the proof of ownership defined in [RFC8928] that already protects the address registration in [RFC8505] to also protect the new subscription mechanism. [RFC8505] is agnostic to the routing protocol in which the address may be redistributed.

As opposed to unicast addresses, there might be multiple registrations from multiple parties for the same address. The router retains one registration per party for each multicast or anycast address but injects the route into the routing protocol only once for each address. The injection happens asynchronously to the registration. On the other hand, the validation exchange with the registrar (6LBR) is still needed if the router checks the right for the host to listen to the anycast or multicast address.

Figure 1 depicts the registration of an anycast or a multicast address. As shown, the 6LBR receives and accepts multiple EDAR messages for the same address, and the address being registered by multiple nodes is not treated as a duplication.

```
     6LoWPAN Node           6LR             6LBR
       (host1)            (router)        (registrar)
          |                  |               |
          |   DMB link       |               |
          |                  |               |
          |  ND-Classic RS   |               |
          |------------------>|              |
          |------------>     |               |
          |------------------------>         |
          |  ND-Classic RA   |               |
          |<------------------|              |
          |                  |               |
          |  NS(EARO)        |               |
          |------------------>|              |
          |                  |     EDAR      |
          |                  |-------------->|
          |                  |               |
          |                  |     EDAC      |
          |                  |<--------------|
          |        NA(EARO)  |
          |<------------------|<inject route> ->
          |                  |
                    ...
       (host2)            (router)           6LBR
          |  NS(EARO)        |               |
          |------------------>|              |
          |                  |               |
          |                  |     EDAR      |
          |                  |-------------->|
          |                  |               |
          |                  |     EDAC      |
          |                  |<--------------|
          |        NA(EARO)  |               |
          |<------------------|              |
                    ...
       (host1)            (router)
          |  NS(EARO)        |               |
          |------------------>|              |
          |                  |               |
          |        NA(EARO)  |               |
          |<------------------|              |
                    ...
          |                  |<maintain route> ->
                    ...
```

Figure 1: Registration Flow for an Anycast or Multicast Address

In classical networks, [RFC8505] may be used for an ND proxy operation as specified in [RFC8929] or redistributed in a full-fledged routing protocol such as what might be done in BGP for Ethernet VPN [MAC-SIGNALING] or in the Routing in Fat Trees (RIFT) protocol [RIFT]. The device mobility can be gracefully supported as long as the routers can exchange and make sense of the sequence counter in the TID field of the EARO.

In the case of LLNs, RPL [RFC6550] is the routing protocol of choice and [RFC9010] specifies how the unicast address advertised with [RFC8505] is redistributed in RPL. This specification also provides RPL extensions for anycast and multicast address operation and redistribution. In the RPL case, and unless specified otherwise, the behavior is the same as it is for unicast for the 6LBR that acts as RPL Root, the intermediate routers Down the RPL graph, the 6LRs that act as access routers, and the 6LNs that are the RPL-unaware destinations. In particular, forwarding a packet happens as specified in Section 11 of [RFC6550], including loop avoidance and detection, though in the multicast case, multiple copies might be generated.

[RFC8505] is a prerequisite to this specification. A node that implements this **MUST** also implement [RFC8505]. This specification modifies existing options and updates the associated behaviors to enable the registration for multicast addresses as an extension to [RFC8505]. As with the registration of a unicast address, the subscription to anycast and multicast addresses between a node and its router(s) is agnostic (meaning it is independent) from the routing protocol in which this information may be redistributed or aggregated by the router to other routers. However, protocol extensions would be needed in the protocol when multicast services are not available.

This specification also Extends [RFC6550] and [RFC9010] to add multicast ingress replication (IR) in Non-Storing mode and anycast support in both Storing and Non-Storing modes in the case of a route-over multilink subnet based on the RPL routing protocol. A 6LR that implements the RPL extensions specified herein **MUST** also implement [RFC9010].

Figure 2 illustrates the typical scenario of an LLN as a single IPv6 subnet, with a 6LBR that acts as Root for RPL operations and maintains a registry of the active registrations as an abstract data structure called an "Address Registrar" for 6LoWPAN ND.

The LLN may be a hub-and-spoke access link such as (Low-Power) Wi-Fi [IEEE-802.11] and (Low-Energy) Bluetooth [IEEE-802.15.1] or a Route-Over LLN such as the Wi-SUN [Wi-SUN] and IPv6 over the TSCH mode of IEEE 802.15.4 (6TiSCH) [RFC9030] meshes that leverage 6LoWPAN [RFC4919] [RFC6282] and RPL [RFC6550] over IEEE 802.15.4 [IEEE-802.15.4].

```
                 |
     ----+-------+------------
         |     Wire side
      +------+
      | 6LBR |
      |(Root)|
      +------+
      o  o  o  Wireless side
  o   o o   o  o o
 o  o  o o   o  o  o
o  o  o   LLN  o   +---+
  o  o   o  o   o  |6LR|
  o o  o o   o     +---+
   o   o   o o o  o    z
  o  o oo o  o        +---+
         o            |6LN|
                      +---+
```

Figure 2: Wireless Mesh

A leaf acting as a 6LN registers its unicast addresses to a RPL router acting as a 6LR using a Layer 2 unicast NS message with an EARO as specified in [RFC8505]. The registration state is periodically renewed by the Registering Node before the lifetime indicated in the EARO expires. As for unicast IPv6 addresses, the 6LR uses an EDAR and then an EDAC exchange with the 6LBR to notify the 6LBR of the presence of the listeners.

This specification updates the EARO with a new 2-bit field, the P-Field, as detailed in Section 7.1. The existing R flag that requests reachability for the Registered Address gets new behavior. With this extension, the 6LNs can now subscribe to the anycast and multicast addresses they listen to, using a new P-Field in the EARO to signal that the registration is for a multicast address. Multiple 6LNs may subscribe the same multicast address to the same 6LR. Note the use of the term "subscribe": this means that when using the EARO registration mechanism, a node registers the unicast addresses that it owns but subscribes to the multicast addresses that it listens to.

With this specification, the 6LNs can also subscribe the anycast addresses they accept using a new P-Field in the EARO to signal that the registration is for an anycast address. For multicast addresses, multiple 6LNs may subscribe the same anycast address to the same 6LR.

If the R flag is set in the subscription of one or more 6LNs for the same address, the 6LR injects the anycast addresses and multicast addresses of a scope larger than the link-scope in RPL, based on the longest subscription lifetime across the active subscriptions for the address.

In the RPL Storing Mode of Operation with multicast support (Section 12 of [RFC6550]), the DAO messages for the multicast address percolate along the RPL-preferred parent tree and mark a subtree that becomes the multicast tree for that multicast address, with 6LNs that subscribed to the address as the leaves. As prescribed in Section 12 of [RFC6550], the 6LR forwards a multicast packet as an individual unicast Medium Access Control (MAC) frame to each peer along the multicast tree, except to the node it received the packet from.

In the new RPL Non-Storing Mode of Operation with ingress replication multicast support that is introduced here, the DAO messages announce the multicast addresses as Targets, and never as Transits. The multicast distribution is an IR whereby the Root encapsulates the multicast packets to all the 6LRs that are transit for the multicast address, using the same source-routing header as for unicast targets attached to the respective 6LRs.

LLN links are typically Direct MAC Broadcast (DMB) (see more in [IPv6-OVER-WIRELESS]) with no emulation to increase range (over multiple radio hops) or reliability. In such links, broadcasting is unreliable and asynchronous transmissions force a listener to remain awake, so asynchronous broadcasting is generally inefficient. Thus, the expectation is that whenever possible, the 6LRs deliver the multicast packets as individual unicast MAC frames to each of the 6LNs that subscribed to the multicast address. On the other hand, in a network where nodes do not sleep, asynchronous broadcasting may still help recovering faster when state is lost.

With this specification, anycast addresses can be injected in RPL in both Storing and Non-Storing modes. In Storing mode, the RPL router accepts DAO messages from multiple children for the same anycast address, but it only forwards a packet to one of the children. In Non-Storing mode, the Root maintains the list of all the RPL nodes that announced the anycast address as Target, but it forwards a given packet to only one of them.

Operationally speaking, deploying a new MOP means that one cannot update a live network. The network administrator must create a new instance with MOP 5 and migrate nodes to that instance by allowing them to join it.

For backward compatibility, this specification allows building a single DODAG signaled as MOP 1 that conveys anycast, unicast, and multicast packets using the same source-routing mechanism; see more in Section 11.

It is also possible to leverage this specification between the 6LN and the 6LR for the registration of unicast, anycast, and multicast IPv6 addresses in networks that are not necessarily LLNs and/or where the routing protocol between the 6LR and its peer routers is not necessarily RPL. In that case, the distribution of packets between the 6LR and the 6LNs may effectively rely on a broadcast or multicast support at the lower layer (e.g., using this specification as a replacement to MLD in an Ethernet-bridged domain and still using either a plain MAC-layer broadcast or snooping of this protocol to control the flooding). It may also rely on overlay services to optimize the impact of Broadcast, Unknown, and Multicast (BUM) traffic over a fabric, e.g., registering with [MAC-SIGNALING] and forwarding with [RFC9574].

For instance, it is possible to operate a RPL Instance in the new Non-Storing Mode of Operation with ingress replication multicast support (while possibly signaling a MOP of 1) and use "Multicast Protocol for Low-Power and Lossy Networks (MPL)" [RFC7731] for the multicast operation. MPL floods the DODAG with the multicast messages independently of the RPL DODAG topologies. Two variations are possible:

- In one possible variation, all the 6LNs set the R flag in the EARO for a multicast target, upon which the 6LRs send a unicast DAO message to the Root; the Root filters out the multicast messages for which there is no listener and only floods when a listener exists.

- In a simpler variation, the 6LNs do not set the R flag and the Root floods all the multicast packets over the whole DODAG. Using a configuration mechanism, it is also possible to control the behavior of the 6LR to ignore the R flag. It can be configured to either always or never send the DAO message and/or to control the Root and specify which groups it should flood or not flood.

Note that if the configuration instructs the 6LR not to send the DAO message, then MPL can be used in conjunction with the RPL Storing mode as well.

4. Amending RFC 4861

Section 7.1 of [RFC4861] requires silently discarding NS and NA packets when the Target Address is a multicast address. This specification Amends [RFC4861] by allowing the advertisement of multicast and anycast addresses in the Target Address field when the NS message is used for a registration, per Section 5.5 of [RFC8505].

5. Extending RFC 7400

This specification Extends "6LoWPAN-GHC: Generic Header Compression for IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs)" [RFC7400] by defining a new capability bit for use in the 6CIO. [RFC7400] was already extended by [RFC8505] for use in IPv6 ND messages.

The new "Registration for Unicast, Multicast, and Anycast Addresses Supported" X flag indicates to the 6LN that the 6LR accepts unicast, multicast, and anycast address registrations as specified in this document and will ensure that packets for the Registered Address will be routed to the 6LNs that registered with the R flag set appropriately.

Figure 3 illustrates the X flag in its position (8, counting 0 to 15 in network order in the 16-bit array); see Section 14.6 for the IANA registration of capability bits.

```
 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    |X|A|D|L|B|P|E|G|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                           Reserved                            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 3: New Capability Bits in the 6CIO

New Option Field:

X: This is a 1-bit flag for "Registration for Unicast, Multicast, and Anycast Addresses Supported".

6. Amending RFC 6550

This specification Amends [RFC6550] to mandate the use of the ROVR field as the indication of the origin of a Target advertisement in RPL DAO messages, as specified as an option in Section 6.1 of [RFC9010].

This specification Extends [RFC6550] with a new P-Field in the RPL Target Option (RTO).

The specification also Amends the behaviors of the Modes of Operation MOP 1 and MOP 3 and Extends [RFC6550] with a new MOP 5.

6.1. Mandating the ROVR Field

For anycast and multicast advertisements (in NS or DAO messages), multiple origins may subscribe to the same address, in which case the multiple advertisements from the different or unknown origins are merged by the common parent; in that case, the common parent becomes the origin of the merged advertisements and uses its own ROVR value. On the other hand, a parent that propagates an advertisement from a single origin uses the original ROVR in the propagated RTO, as it does for unicast address advertisements, so the origin is recognized across multiple hops.

[RFC6550] uses the Path Sequence in the Transit Information Option (TIO) to retain only the freshest unicast route and remove the stale ones, e.g., in the case of mobility. [RFC9010] copies the Transaction ID (TID) from the EARO into the Path Sequence and the ROVR field into the associated RTO. This way, it is possible to identify both the Registering Node and the order of registration in RPL for each individual advertisement, so the most recent path and lifetime values are used.

This specification Extends [RFC6550] for anycast and multicast advertisements to require that the Path Sequence be used between, and only between, advertisements for the same Target and from the same origin (i.e., with the same ROVR value). In that case, only the freshest advertisement is retained, but the freshness comparison cannot apply if the origin is not determined (i.e., the origin did not support this specification).

[RFC6550] uses the Path Lifetime in the TIO to indicate the remaining time for which the advertisement is valid for unicast route determination, and a Path Lifetime value of 0 invalidates that route. [RFC9010] maps the Address Registration lifetime in the EARO and the Path Lifetime in the TIO so they are comparable when both forms of advertisements are received.

The RPL router that merges multiple advertisements for the same anycast or multicast addresses **MUST** use and advertise the longest remaining lifetime across all the origins of the advertisements for that address. When the lifetime expires, the router sends a no-path DAO message (i.e., the lifetime is 0) using the same value for the ROVR value as for the previous advertisements. This value refers to either the single descendant that advertised the Target if there is only one or the router itself if there is more than one.

Note that the Registration Lifetime, TID, and ROVR fields are also placed in the EDAR message so the state created by the EDAR is also comparable with that created upon an NS(EARO) or a DAO message. For simplicity, the text below mentions only NS(EARO) but it also applies to EDAR.

6.2. Updating MOP 3

RPL supports multicast operations in the Storing Mode of Operation with multicast support (MOP 3), which provides source-independent multicast routing in RPL, as prescribed in Section 12 of [RFC6550]. MOP 3 is a Storing Mode of Operation. This operation builds a multicast tree within the RPL DODAG for each multicast address. This specification provides additional details for the MOP 3.

The expectation in MOP 3 is that the unicast traffic also follows the Storing Mode of Operation. However, this is rarely the case in LLN deployments of RPL where the Non-Storing Mode of Operation (MOP 1) is the norm. Though it is preferred to build separate RPL Instances, one in MOP 1 and one in MOP 3, this specification allows hybrid use of the Storing mode for multicast and the Non-Storing mode for unicast in the same RPL Instance, as is elaborated in more detail in Section 11.

For anycast and multicast advertisements, including MOP 3, the ROVR field is placed in the RTO as specified in [RFC9010] for both MOP 3 and MOP 5 as it is for unicast advertisements.

Though it was implicit with [RFC6550], this specification clarifies that the freshness comparison based on the Path Sequence is not used when the origin cannot be determined, which occurs in the case of multiple subscriptions of a multicast or unicast address. The comparison is to be used only between advertisements from the same origin, which is either an individual subscriber or a descendant that merged multiple advertisements.

A RPL router maintains a remaining Path Lifetime for each DAO message that it receives for a multicast target and sends its own DAO message for that target with the longest remaining lifetime across its listening children. If the router has only one descendant listening, it propagates the TID and ROVR as received. Conversely, if the router merges multiple advertisements (possibly including one for itself as a listener), the router uses its own ROVR and TID values. This implies a possible transition of ROVR and TID values when the number of listening children changes from one to more or back to one, which should not be considered as an error or a change of ownership by the parents above.

6.3. New Non-Storing Multicast MOP

This specification adds a Non-Storing Mode of Operation with ingress replication multicast support RPL (as assigned by IANA; see Section 14.5) whereby the Non-Storing Mode DAO to the Root may advertise a multicast address in the RTO, whereas the TIO cannot.

In that mode, the RPL Root performs an IR operation on the multicast packets. This means that it transmits one copy of each multicast packet to each 6LR that is a transit for the multicast target, using the same source-routing header and encapsulation as it would for a unicast packet for a RPL-Unaware Leaf (RUL) attached to that 6LR.

For the intermediate routers, the packet appears as any source-routed unicast packet. The difference shows only at the 6LR, which terminates the source-routed path and forwards the multicast packet to all 6LNs that registered for the multicast address.

For a packet that is generated by the Root, the Root builds a source-routing header as shown in Section 8.1.3 of [RFC9008], but for which the last and only the last address is multicast. For a packet that is not generated by the Root, the Root encapsulates the multicast packet as per Section 8.2.4 of [RFC9008]. In that case, the outer header is purely unicast, and the encapsulated packet is purely multicast.

For anycast and multicast advertisements in NA messages (at the 6LR) and DAO messages (at the Root), as discussed in Section 6.2, the freshness comparison based on the TID field is applied only between messages from the same origin, as determined by the same value in the ROVR field.

The Root maintains a remaining Path Lifetime for each advertisement it receives, and a 6LR generates the DAO message for multicast addresses with the longest remaining lifetime across its registered 6LNs, using its own ROVR and TID when multiple 6LNs have subscribed or when the 6LR is a subscriber.

This specification allows enabling the operation in a MOP 1 brown field for this new mode as well; see more in Section 11.

6.4. RPL Anycast Operation

With multicast, the address has a recognizable format, and a multicast packet is to be delivered to all the active subscribers. In contrast, the format of an anycast address is not distinguishable from that of a unicast address. A legacy node may issue a DAO message without setting the P-Field to 2; the unicast behavior may apply to anycast traffic within a portion of the network, but the packets will still be delivered. That message will be undistinguishable from a unicast advertisement, and the anycast behavior in the data plane can only happen if all the nodes that advertise the same anycast address are synchronized with the same TID. That way, the multiple paths can remain in the RPL DODAG.

With the P-Field set to 2, this specification alleviates the issue of synchronizing the TIDs and ROVR fields. As for multicast, the freshness comparison based on the TID (in the EARO) and the Path Sequence (in the TIO) is ignored unless the messages have the same origin; this is inferred by the same ROVR in the RTO and/or the EARO, and the latest value of the lifetime is retained for each origin.

A RPL router that propagates an advertisement from a single origin uses the ROVR and Path Sequence from that origin, whereas a router that merges multiple subscriptions uses its own ROVR and Path Sequence and the longest lifetime over the different advertisements. A target is routed as anycast by a parent (or the Root) that received at least one DAO message for that target with the P-Field set to 2.

As opposed to multicast, the anycast operation described herein applies to both addresses and prefixes, and the P-Field can be set to 2 for both. An external destination (such as an address or prefix) that may be injected as a RPL Target from multiple border routers should be injected as anycast in RPL to enable load balancing. In contrast, a mobile target that is multihomed should be advertised as unicast over the multiple interfaces to favor the TID comparison instead of multipath load balancing.

For either multicast or anycast, there can be multiple subscriptions from multiple origins, each using a different value of the ROVR field that identifies the individual subscription. The 6LR maintains a subscription state per value of the ROVR for each multicast or anycast address, but it injects the route into RPL only once for each address. In the case of a multicast address, this occurs only if its scope is larger than the link-scope (three or more). Since the subscriptions are considered separate, the check on the TID that acts as the subscription sequence only applies to the subscription with the same ROVR.

Like the 6LR, a RPL router in Storing mode propagates the merged advertisement to its parent(s) in DAO messages once and only once for each address, but it retains a routing table entry for each of the children that advertised the address.

When forwarding multicast packets Down the DODAG, the RPL router copies all the children that advertised the address in their DAO messages. In contrast, when forwarding anycast packets Down the DODAG, the RPL router **MUST** copy one and only one of the children that advertised the address in their DAO messages and forward it to one parent if there is no such child.

6.5. New Registered Address Type Indicator P-Field

The new Registered Address Type Indicator (RATInd) is created for use in the RTO, the EARO, and the header of EDAR messages. The RATInd indicates whether an address is unicast, multicast, or anycast. The new 2-bit P-Field is defined to transport the RATInd in different protocols.

The P-Field can take the values shown in Table 2.

The intent for the value of 3 is a prefix registration (see [REGISTRATION]), which is expected to be published after this specification. At the time of this writing, RPL already advertises prefixes, and treats unicast addresses as prefixes with a length of 128, so it does not need that new value. On the other hand, 6LoWPAN ND does not, so the value of 3 (meaning prefix registration) will not be processed adequately. As a result:

- When the value of 3 is received in an RTO (see Section 6.6), this value **MUST** be ignored by the receiver (meaning it is treated as a value of 0) but the message is processed normally (as per [RFC6550] and [RFC9010]).
- In the case of an EARO (see Section 7.1) or an EDAR (see Section 7.2), the message **MUST** be dropped, and the receiving node **MAY** either reply with a status of 12 "Invalid Registration" or remain silent.

6.6. New RPL Target Option P-Field

[RFC6550] recognizes a multicast address by its format (as specified in Section 2.7 of [RFC4291]) and applies the specified multicast operation if the address is recognized as multicast. This specification updates [RFC6550] to add the 2-bit P-Field (see Section 6.5) to the RTO to indicate that the Target Address is to be processed as unicast, multicast, or anycast.

- An RTO that has the P-Field set to 0 is called a unicast RTO.
- An RTO that has the P-Field set to 1 is called a multicast RTO.
- An RTO that has the P-Field set to 2 is called an anycast RTO.

The suggested position for the P-Field is 2 counting from 0 to 7 in network order as shown in Figure 4, based on Figure 4 of [RFC9010], which defines the flags in positions 0 and 1:

```
     0                   1                   2                   3
     0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    |   Type = 0x05 | Option Length |F|X| P |ROVRsz | Prefix Length |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    |                                                               |
    |                Target Prefix (Variable Length)                |
    .                                                               .
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    |                                                               |
   ...            Registration Ownership Verifier (ROVR)           ...
    |                                                               |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 4: Format of the RPL Target Option (RTO)

New and updated Option Field:

P: This is a 2-bit field; see Section 6.5.

7. Extending RFC 8505

This specification Extends [RFC8505] by adding the concept of a subscription for anycast and multicast addresses and creating a new field called the P-Field in the EARO and in the EDAR and EDAC messages to signal the type of registration.

7.1. Placing the New P-Field in the EARO

Section 4.1 of [RFC8505] defines the EARO as an extension to the ARO defined in [RFC6775]. This specification adds a new P-Field that is placed in the EARO flags and is set as follows:

- The P-Field is set to 1 to signal that the Registered Address is a multicast address. When the P-Field is 1 and the R flag is set to 1 as well, the 6LR that conforms to this specification joins the multicast stream (e.g., by injecting the address in the RPL multicast support that is extended in this specification for the Non-Storing mode).

- The P-Field is set to 2 to signal that the Registered Address is an anycast address. When the P-Field is 2 and the R flag is 1, the 6LR that conforms to this specification injects the anycast address in the routing protocol(s) that it participates in (e.g., in the RPL anycast support that is introduced in this specification for both the Storing and Non-Storing modes).

Figure 5 illustrates the P-Field in its position (2, counting 0 to 7 in network order in the 8-bit array); see Section 14.1 for the IANA registration of P-Field values.

```
  0                   1                   2                   3
  0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |     Type      |     Length    |    Status     |    Opaque     |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |Rsv| P | I |R|T|     TID       |     Registration Lifetime     |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                                                               |
...          Registration Ownership Verifier (ROVR)            ...
 |                                                               |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 5: Extended Address Registration Option (EARO) Format

New and updated Option Fields:

Rsv: This is a 2-bit field. It is reserved and **MUST** be set to 0 and ignored by the receiver.

P: This is a 2-bit P-Field; see Section 6.5.

7.2. Placing the New P-Field in the EDAR Message

Section 4 of [RFC6775] provides the same format for DAR and DAC messages but the Status field is only used in DAC messages and has to be set to 0 in DAR messages. [RFC8505] extends the DAC message as an EDAC but does not change the Status field in the EDAR.

This specification repurposes the Status field in the EDAR as a Flags field. It adds a new P-Field to the EDAR flags field to match the P-Field in the EARO and signal the new types of registration. The EDAC message is not modified.

Figure 6 illustrates the P-Field in its position (0, counting 0 to 7 in network order in the 8-bit array); see Section 14.2 for the IANA registration of EDAR message flags.

```
     0                   1                   2                   3
     0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    |     Type      |CodePfx|CodeSfx|          Checksum             |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    | P | Reserved  |     TID       |     Registration Lifetime     |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    |                                                               |
   ...            Registration Ownership Verifier (ROVR)           ...
    |                                                               |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    |                                                               |
    +                                                               +
    |                                                               |
    +                       Registered Address                      +
    |                                                               |
    +                                                               +
    |                                                               |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 6: Extended Duplicate Address Request (EDAR) Message Format

New and updated Option Fields:

Reserved: This is a 6-bit field. It is reserved and **MUST** be set to 0 and ignored by the receiver.

P: This is a 2-bit field; see Section 6.5.

7.3. Registration Extensions

[RFC8505] specifies the following behaviors:

- A router that expects to reboot may send a final RA message, upon which nodes should subscribe elsewhere or redo the subscription to the same router upon reboot. In all other cases, a node reboot is silent. When the node comes back to life, existing registration state might be lost if it was not persisted, e.g., in persistent memory.
- The registration method is specified only for unicast addresses.
- The 6LN must register all its ULAs and GUAs with an NS(EARO) message.
- The 6LN may set the R flag in the EARO to obtain return reachability services by the 6LR, e.g., through ND proxy operations or by injecting the route in a route-over subnet.
- the 6LR maintains a registration state per Registered Address, including an NCE with the Link-Layer Address (LLA) of the Registered Node (the 6LN here).

This specification Amends the above behaviors and Extends them with the following behaviors:

- The concept of subscription is introduced for anycast and multicast addresses as an extension to the registration of a unicast address. The respective operations are similar from the perspective of the 6LN, but they show important differences on the router side, which maintains a separate state for each origin and merges them in its own advertisements.

- New ARO Statuses are introduced to indicate a "Registration Refresh Request" and an "Invalid Registration" (see Table 8).

  The former status is used in asynchronous NA(EARO) messages to indicate to peer 6LNs that they are requested to reregister all addresses that were previously registered to the originating node. The NA message may be sent to a unicast or a multicast link-scope address and should be contained within the L2 range where nodes may have effectively registered or, respectively, subscribed to this router (e.g., a radio broadcast domain). The latter is generic to any error in the EARO and is used, for example, to report that the P-Field is not consistent with the Registered Address in NS(EARO) and EDAR messages.

  A router that wishes to refresh its state (e.g., upon reboot or in any situation where it may have missed a registration or lost a registration state) **SHOULD** send an asynchronous NA(EARO) with this new status value. Failure to do so will delay the recovery of the network until the next periodic registration by the attached 6LNs and packets may be lost until then. That asynchronous multicast NA(EARO) **MUST** be sent to the all-nodes link-scope multicast address (ff02::1), and the Target **MUST** be set to the link-local address that was exposed previously by this node to accept registrations.

  The TID field in the multicast NA(EARO) message is the one associated to the Target and follows the same rules as the TID in the NS(EARO) message for the same Target; see Section 5.2 of [RFC8505], which points to Section 7.2 of [RFC6550] for the lollipop mechanism used in the TID operation. It is incremented by the sender each time it sends a new series of NS and/or NA messages with the EARO about the Target. The TID indicates a reboot when it is in the "straight" part of the lollipop, between the initial value and 255. After that, the TID remains below 128 as long as the device is alive. An asynchronous multicast NA(EARO) with a TID below 128 **MUST NOT** be considered as indicating a reboot.

  The asynchronous multicast NA(EARO) indicating a "Registration Refresh Request" **MAY** be reissued a few times within a short period, to increase the chances that the message is received by all registered nodes despite the unreliable transmissions within the LLN; the TID **MUST** be incremented each time. The receiver 6LN **MUST** consider that multiple NA(EARO) messages indicating a "Registration Refresh Request" from the same 6LR received within that short period with comparable and increasing TID values (i.e., their absolute difference is less than the SEQUENCE_WINDOW; see Section 7.2 of [RFC6550]) are in fact indicative of the same request. The 6LN **MUST** process one and only one of the series of messages. If the TIDs are desynchronized (not comparable) or decreased, then the NA(EARO) is considered as a new request and it **MUST** be processed.

  The multicast NA(EARO) **SHOULD** be resent enough times for the TID to be issued with the value of 255 so the next NA(EARO) after the initial series is outside the lollipop and is not confused with a reboot. By default, the TID initial setting after boot is 252, the SEQUENCE_WINDOW is 4, the duration of the short period is 10 seconds, the interval between retries is 1 second, and the number of retries is 3. To reach 255 at boot time, the sender **MAY** either issue at least 4 NA messages, skip a TID value, or start with a value that is more than 252. The best values for the short period, the number of retries, and the TID initial setting depend on the environment and **SHOULD** be configurable.

- A new IPv6 ND Consistent Uptime Option (CUO) is introduced to be placed in IPv6 ND messages. The CUO allows figuring out the state consistency between the sender and the receiver. For instance, a node that rebooted needs to reset its uptime to 0. A router that changed information like a prefix information option has to advertise an incremented state sequence. To that effect, the CUO carries a Node State Sequence Information (NSSI) and a Consistent Uptime. See Section 10 for the option details.

  A node that receives the CUO checks whether it is indicative of a desynchronization between peers. A peer that discovers that a router has changed should reassess which addresses it formed based on the new PIOs from that router and resync the state that it installed in the router (e.g., the registration state for its addresses). In the process, the peer may attempt to:

  - form new addresses and register them,
  - deprecate old addresses and deregister them using a Lifetime of 0, and
  - reform any potentially lost state (e.g., by registering again an existing address that it will keep using).

  A loss of state is inferred if the Consistent Uptime of the peer is less than the time since the state was installed, or if the NSSI is incremented for a Consistent Uptime.

- Registration for multicast and anycast addresses is now supported. The P-Field is added to the EARO to signal when the Registered Address is anycast or multicast. The value of the P-Field is not consistent with the Registered Address if:

  - the Registered Address is a multicast address (Section 2.4 of [RFC4291]) and the P-Field indicates a value that is not 1, or
  - the Registered Address is not a multicast address and the P-Field indicates a value that is 1.

  If this occurs, then the message, NS(EARO) or EDAR, **MUST** be dropped, and the receiving node **MAY** either reply with a status of 12 "Invalid Registration" or remain silent.

- The Status field in the EDAR message that was reserved and not used in [RFC8505] is repurposed to transport the flags to signal multicast and anycast.
- The 6LN **MUST** also subscribe all the IPv6 multicast addresses that it listens to, and it **MUST** set the P-Field to 1 in the EARO for those addresses. The one exception is the all-nodes link-scope multicast address ff02::1 [RFC4291], which is implicitly registered by all nodes, meaning that all nodes are expected to accept messages sent to ff02::1 but are not expected to register it.
- The 6LN **MAY** set the R flag in the EARO to obtain the delivery of the multicast packets by the 6LR (e.g., by MLD proxy operations, or by injecting the address in a route-over subnet or in the Protocol Independent Multicast [RFC7761] protocol).
- The 6LN **MUST** also subscribe all the IPv6 anycast addresses that it supports, and it **MUST** set the P-Field in the EARO to 2 for those addresses.
- The 6LR and the 6LBR are extended to accept more than one subscription for the same address when it is anycast or multicast, since multiple 6LNs may subscribe to the same address of these types. In both cases, the ROVR in the EARO uniquely identifies a registration within the namespace of the Registered Address.

- The 6LR **MUST** also consider that all the nodes that registered an address to it (as known by the Source Link-Layer Address Option (SLLAO)) also registered ff02::1 [RFC4291] to the all-nodes link-scope multicast address.
- The 6LR **MUST** maintain a subscription state per tuple (IPv6 address, ROVR) for both anycast and multicast types of addresses. It **SHOULD** notify the 6LBR with an EDAR message, unless it determined that the 6LBR is legacy and does not support this specification. In turn, the 6LBR **MUST** maintain a subscription state per tuple (IPv6 address, ROVR) for both anycast and multicast types of address.

8. Extending RFC 9010

[RFC9010] specifies the following behaviors:

- The 6LR has no specified procedure to inject multicast and anycast routes in RPL even though RPL supports multicast.
- Upon a registration with the R flag set to 1 in the EARO, the 6LR injects the address in the RPL unicast support.
- Upon receiving a packet directed to a unicast address for which it has an active registration, the 6LR delivers the packet as a unicast Layer 2 frame to the LLA of the node that registered the unicast address.

This specification Extends [RFC9010] by adding the following behavior:

- Upon a subscription with the R flag and the P-Field both set to 1 in the EARO, if the scope of the multicast address is above link-scope [RFC7346], then the 6LR injects the address in the RPL multicast support and sets the P-Field in the RTO to 1 as well.
- Upon a subscription with the R flag set to 1 and the P-Field set to 2 in the EARO, the 6LR injects the address in the new RPL anycast support and sets the P-Field to 2 in the RTO.
- Upon receiving a packet directed to a multicast address for which it has at least one subscription, the 6LR delivers a copy of the packet as a unicast Layer 2 frame to the LLA of each of the nodes that registered to that multicast address.
- Upon receiving a packet directed to an anycast address for which it has at least one subscription, the 6LR delivers a copy of the packet as a unicast Layer 2 frame to the LLA of exactly one of the nodes that registered to that multicast address.

9. Leveraging RFC 8928

"Address-Protected Neighbor Discovery for Low-Power and Lossy Networks" [RFC8928] was defined to protect the ownership of unicast IPv6 addresses that are registered with [RFC8505].

With [RFC8928], it is possible for a node to autoconfigure a pair of public and private keys and use them to sign the registration of addresses that are either autoconfigured or obtained through other methods.

The first hop router (the 6LR) may then validate a registration and perform source address validation on packets coming from the sender node (the 6LN).

Anycast and multicast addresses are not owned by one node. Multiple nodes may subscribe to the same address. In that context, the method specified in [RFC8928] cannot be used with autoconfigured key pairs to protect a single ownership.

For an anycast or a multicast address, it is still possible to leverage [RFC8928] to enforce the right to subscribe. If [RFC8928] is used, a key pair **MUST** be associated with the address before it is deployed, and a ROVR **MUST** be generated from that key pair as specified in [RFC8928]. The address and the ROVR **MUST** then be installed in the 6LBR so it can recognize the address and compare the ROVR on the first subscription.

The key pair **MUST** then be provisioned in each node that needs to subscribe to the anycast or multicast address, so the node can follow the steps in [RFC8928] to subscribe to the address.

10. Consistent Uptime Option

This specification introduces a new option that characterizes the uptime of the sender. The option may be used by routers in RA messages and by any node in NS, NA, and RS messages. It is used by the receiver to infer whether some state synchronization might be lost (e.g., due to reboot).

```
  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    | Exponent  |  Uptime Mantissa  |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |S|U|   flags   |           NSSI          |      Peer NSSI      |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 7: Consistent Uptime Option (CUO) Format

Type: Assigned by IANA; see Table 9.

Length: 1

Uptime Exponent: A 6-bit unsigned integer and the Exponent to the base 2 of the uptime unit.

Uptime Mantissa: A 10-bit unsigned integer and the mantissa of the uptime value.

S: A 1-bit flag set to 1 to indicate that the sender is low-power and may sleep.

U: A 1-bit flag set to 1 to indicate that the Peer NSSI field is valid; it **MUST** be set to 0 when the message is not unicast and **MUST** be set to 1 when the message is unicast and the sender has an NSSI state for the intended receiver.

flags: 6-bit flags that are reserved and that **MUST** be set to 0 by the sender and ignored by the receiver.

NSSI: A 12-bit unsigned integer that represents the Node State Sequence Information (NSSI). It **MUST** be stored by the receiver if it has a dependency on information advertised or stored at the sender.

Peer NSSI: A 12-bit unsigned integer that echoes the last known NSSI from the peer.

The Consistent Uptime indicates how long the sender has been continuously up and running (though possibly sleeping) without loss of state. It is expressed by the Uptime Mantissa in units of 2 to the power of the Uptime Exponent in milliseconds. The receiver derives the boot time of the sender as the current time minus the sender's Consistent Uptime.

If the boot time of the sender is updated to a newer time, any state that the receiver installed in the sender before the reboot is probably lost. The receiver **MUST** reassess all the state it installed in the server (e.g., any registration) and reinstall if it is still needed.

The U flag not set in a unicast message indicates that the sender has lost all state from this node. If the U flag is set, then the Peer NSSI field can be used to assess which changes the sender missed. For the other way around, any state that was installed in the receiver from information by the sender before it rebooted **MUST** be removed and may or may not be reinstalled later.

The value of the uptime is reset to 0 at some point of the sender's reboot sequence, but it may not still be 0 when the first message is sent, so the receiver must not expect a value of 0 as the signal of a reboot.

Mantissa	Exponent	Resolution	Uptime
1	0	1 ms	1 ms
5	10	1 s	5 s
2	15	30 s	1 min
2	21	33 min	1 hour

Table 1: Consistent Uptime Rough Values

The NSSI **SHOULD** be stored in persistent memory by the sender and incremented when it may have missed or lost state about a peer, or when it has updated some state in a fashion that will impact a peer (e.g., a host formed a new address or a router advertises a new prefix). When persisting is not possible, then the NSSI is randomly generated.

As long as the NSSI remains constant, the cross-dependent state (such as addresses in a host that depend on a prefix in a router) can remain stable, meaning less checks in the receiver. Any change in the value of the NSSI is an indication that the sender updated some state and that the dependent state in the receiver should be reassessed (e.g., addresses that were formed based on an RA with a previous NSSI should be checked, or new addresses may be formed and registered).

11. Operational Considerations

With this specification, a RPL DODAG forms a realm, and multiple RPL DODAGs may be federated in a single RPL Instance administratively. This means that a multicast address that needs to span a RPL DODAG **MUST** use a scope of Realm-Local whereas a multicast address that needs to span a RPL Instance **MUST** use a scope of Admin-Local as discussed in Section 3 of [RFC7346], "IPv6 Multicast Address Scopes".

"IPv6 Addressing of IPv4/IPv6 Translators" [RFC6052] enables embedding IPv4 addresses in IPv6 addresses. The Root of a DODAG may leverage that technique to translate IPv4 traffic in IPv6 and route along the RPL domain. When encapsulating a packet with an IPv4 multicast Destination Address, it **MUST** use a multicast address with the appropriate scope, Realm-Local or Admin-Local.

"Unicast-Prefix-based IPv6 Multicast Addresses" [RFC3306] enables forming 2^{32} multicast addresses from a single /64 prefix. If an IPv6 prefix is associated to an Instance or a RPL DODAG, this provides a namespace that can be used in any desired fashion. For instance, it is possible for a standard defining organization to form its own registry and allocate 32-bit values from that namespace to network functions or device types. When used within a RPL deployment that is associated with a /64 prefix, the IPv6 multicast addresses can be automatically derived from the prefix and the 32-bit value for either a Realm-Local or an Admin-Local multicast address as needed in the configuration.

This specification introduces the new RPL MOP 5. Operationally speaking, deploying a new RPL MOP means that one cannot update a live network. The network administrator must create a new instance with MOP 5 and migrate nodes to that instance by allowing them to join it.

In a "green field" deployment where all nodes support this specification, it is possible to deploy a single RPL Instance using a multicast MOP for unicast, multicast, and anycast addresses.

In a "brown field" where legacy devices that do not support this specification coexist with upgraded devices, it is **RECOMMENDED** to deploy one RPL Instance in any MOP (typically MOP 1) for unicast that legacy nodes can join and a separate RPL Instance dedicated to multicast and anycast operations using a multicast MOP.

To deploy a Storing mode multicast operation using MOP 3 in a RPL domain, it is required that the RPL routers that support MOP 3 have enough density to build a DODAG that covers all the potential listeners and includes the spanning multicast trees that are needed to distribute the multicast flows. This might not be the case when extending the capabilities of an existing network.

In the case of the new Non-Storing multicast MOP, arguably the new support is only needed at the 6LRs that will accept multicast listeners. It is still required that each listener be able to reach at least one such 6LR, so the upgraded 6LRs must be deployed to cover all the 6LNs that need multicast services.

Using separate RPL Instances for unicast traffic on the one hand and for anycast and multicast traffic on the other hand allows for the use of different objective functions; one favors the link quality Up for unicast collection and the other favors Downwards link quality for multicast distribution.

However, this might be impractical in some use cases where the signaling and the state to be installed in the devices are very constrained, the upgraded devices are too sparse, or the devices do not support more multiple instances.

When using a single RPL Instance, MOP 3 expects the Storing Mode of Operation for both unicast and multicast, which is an issue in constrained networks that typically use MOP 1 for unicast. This specification allows a mixed mode that is signaled as MOP 1 in the DIO messages for backward compatibility, where limited multicast and/or anycast is available, under the following conditions:

- There **MUST** be enough density of the 6LRs that support the mixed mode to cover all the 6LNs that require multicast or anycast services. In Storing mode, there **MUST** be enough density of the 6LRs that support the mixed mode to also form a DODAG to the Root.
- The RPL routers that support the mixed mode are configured to operate in accordance with the desired operation in the network.
- The MOP signaled in the RPL DIO messages is MOP 1 to enable the legacy nodes to operate as leaves.
- The support of multicast and/or anycast in the RPL Instance **SHOULD** be signaled by the 6LRs to the 6LN using a 6CIO; see Section 5.
- Alternatively, the support of multicast in the RPL domain can be globally known by other means including configuration or external information such as support of a version of an industry standard that mandates it. In that case, all the routers **MUST** support the mixed mode.

12. Security Considerations

This specification Extends [RFC8505] and [RFC9010] and leverages [RFC9008]. The security sections in these documents also apply to this document. In particular, the link layer **SHOULD** be sufficiently protected to prevent rogue access.

RPL [RFC6550] already supports routing on multicast addresses, whereby the endpoint that subscribes to the group by injecting the multicast address participates as a RPL-Aware Node (RAN) in the RPL. Using an extension of [RFC8505] as opposed to RPL to subscribe the address allows a RPL-Unaware Leaf (RUL) to subscribe as well. As noted in [RFC9010], this provides a better security posture for the RPL network, since the nodes that do not really need to speak RPL, or are not trusted enough to inject RPL messages, can be forbidden from doing so, which bars a number of attack vectors from within RPL. Acting as an RUL, those nodes may still leverage the RPL network through the capabilities that are opened via ND operations. With this specification, a node that needs multicast delivery can now obtain the service in a RPL domain while not being allowed to inject RPL messages.

Compared to [RFC6550], this specification enables tracking the origin of the multicast subscription inside the RPL network. This is a first step to enable a form of Route Ownership Validation (ROV) (see [RFC6811]) in RPL using the ROVR field in the EARO as proof of ownership.

Section 9 leverages [RFC8928] to prevent a rogue node from registering a unicast address that it does not own. The mechanism could be extended to anycast and multicast addresses if the values of the ROVR they use are known in advance, but how this is done is not in scope for this specification. One way would be to authorize the ROVR of the valid users in advance. A less preferred way would be to synchronize the ROVR and TID values across the valid subscribers as preshared key material.

In the latter case, it could be possible to update the keys associated to an address in all the 6LNs, but the flow is not clearly documented and may not complete in due time for all nodes in LLN use cases. It may be simpler to install an all-new address with new keys over a period of time, and switch the traffic to that address when the migration is complete.

13. Backward Compatibility

A legacy 6LN will not subscribe multicast addresses, and the service will be the same when the network is upgraded. A legacy 6LR will not set the X flag in the 6CIO, and an upgraded 6LN will not subscribe multicast addresses.

Upon receiving an EDAR message, a legacy 6LBR may not realize that the address being registered is anycast or multicast and will return that it is a duplicate in the EDAC status. The 6LR **MUST** ignore a duplicate status in the EDAC for anycast and multicast addresses.

As detailed in Section 11, it is possible to add multicast on an existing MOP 1 deployment.

The combination of a multicast address and the P-Field set to 0 in an RTO in a MOP 3 RPL Instance is an indication to the receiver that supports this specification (the parent) that the sender (child) does not support this specification. However, the RTO is accepted and processed as if the P-Field was set to 1 for backward compatibility.

When the DODAG is operated in MOP 3, a legacy node will not set the P-Field and still expect multicast service as specified in Section 12 of [RFC6550]. In MOP 3, an RTO that is received with a target that is multicast and the P-Field set to 0 **MUST** be considered as multicast and **MUST** be processed as if the P-Field is set to 1.

14. IANA Considerations

IANA has made changes under the "Internet Control Message Protocol version 6 (ICMPv6) Parameters" [IANA.ICMP] and "Routing Protocol for Low Power and Lossy Networks (RPL)" [IANA.RPL] registry groupings; see details in the subsections that follow.

14.1. New P-Field Values Registry

IANA has created a new "P-Field Values" registry under the "Internet Control Message Protocol version 6 (ICMPv6) Parameters" registry group to store the expression of the RATInd as a P-Field.

The registration procedure is Standards Action [RFC8126]. The initial allocations are as indicated in Table 2:

Value	Registered Address Type Indicator	Reference
0	Registration for a Unicast Address	RFC 9685
1	Registration for a Multicast Address	RFC 9685
2	Registration for an Anycast Address	RFC 9685
3	Unassigned	RFC 9685

Table 2: P-Field Values Registry

14.2. New EDAR Message Flags Registry

IANA has created a new "EDAR Message Flags" registry under the "Internet Control Message Protocol version 6 (ICMPv6) Parameters" registry group.

The registration procedure is IETF Review or IESG Approval [RFC8126]. The initial allocations are as indicated in Table 3:

Bit Number	Meaning	Reference
0-1	P-Field (2 bits)	RFC 9685, Section 14.1
2-7	Unassigned	

Table 3: EDAR Message Flags Registry

14.3. New Address Registration Option Flags

IANA has made an addition to the "Address Registration Option Flags" registry [IANA.ICMP.ARO.FLG] under the "Internet Control Message Protocol version 6 (ICMPv6) Parameters" registry group as indicated in Table 4:

Bit Number	Description	Reference
2-3	P-Field (2 bits)	RFC 9685, Section 14.1

Table 4: New Address Registration Option Flags

14.4. New RPL Target Option Flags

IANA has made an addition to the "RPL Target Option Flags" registry [IANA.RPL.RTO.FLG] under the "Routing Protocol for Low Power and Lossy Networks (RPL)" registry group as indicated in Table 5:

Bit Number	Capability Description	Reference
2-3	P-Field (2 bits)	RFC 9685, Section 14.1

Table 5: New RPL Target Option Flags

14.5. New RPL Mode of Operation

IANA has made an addition to the "Mode of Operation" registry [IANA.RPL.MOP] under the "Routing Protocol for Low Power and Lossy Networks (RPL)" registry group as indicated in Table 6:

Value	Description	Reference
5	Non-Storing Mode of Operation with ingress replication multicast support	RFC 9685

Table 6: New RPL Mode of Operation

14.6. New 6LoWPAN Capability Bit

IANA has made an addition to the "6LoWPAN Capability Bits" registry [IANA.ICMP.6CIO] under the "Internet Control Message Protocol version 6 (ICMPv6) Parameters" registry group as indicated in Table 7:

Bit	Description	Reference
8	X flag: Registration for Unicast, Multicast, and Anycast Addresses Supported	RFC 9685

Table 7: New 6LoWPAN Capability Bit

14.7. New Address Registration Option Status Values

IANA has made additions to the "Address Registration Option Status Values" registry [IANA.ICMP.ARO.STAT] under the "Internet Control Message Protocol version 6 (ICMPv6) Parameters" registry group as indicated in Table 8:

Value	Description	Reference
11	Registration Refresh Request	RFC 9685

Value	Description	Reference
12	Invalid Registration	RFC 9685

Table 8: New Address Registration Option Status Values

14.8. New IPv6 Neighbor Discovery Option Format

IANA has made an addition to the "IPv6 Neighbor Discovery Option Formats" registry under the "Internet Control Message Protocol version 6 (ICMPv6) Parameters" registry group as indicated in Table 9:

Type	Description	Reference
42	Consistent Uptime Option	RFC 9685

Table 9: New IPv6 Neighbor Discovery Option Format

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Author's Address

Pascal Thubert (EDITOR)
06330 Roquefort-les-Pins
France
Email: pascal.thubert@gmail.com