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Root initiated routing state in RPL
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Abstract

This document extends RFC 6550, RFC 6553, and RFC 8138 to enable a RPL Root to install and maintain Projected Routes within its DODAG, along a selected set of nodes that may or may not include itself, for a chosen duration. This potentially enables routes that are more optimized or resilient than those obtained with the classical distributed operation of RPL, either in terms of the size of a Routing Header or in terms of path length, which impacts both the latency and the packet delivery ratio.

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1. Introduction

RPL, the "Routing Protocol for Low Power and Lossy Networks" [RPL] (LLNs), is an anisotropic Distance Vector protocol that is well-suited for application in a variety of low energy Internet of Things (IoT) networks where stretched P2P paths are acceptable vs. the signaling and state overhead involved in maintaining the shortest paths across.

RPL forms Destination Oriented Directed Acyclic Graphs (DODAGs) in which the Root often acts as the Border router to connect the RPL domain to the IP backbone. Routers inside the DODAG route along that graph up towards the Root for the default route and down towards destinations in the RPL domain for more specific routes. This specification expects as a pre-requisite a pre-existing RPL Instance with an associated DODAG and RPL Root, which are referred to as main Instance, main DODAG and main Root respectively. The main Instance is operated in RPL Non-Storing Mode of Operation (MOP).

With this specification, an abstract routing function called a Path Computation Element [PCE] (e.g., located in an central controller or collocated with the main Root) interacts with the main Root to compute Peer-to-Peer (P2P) paths within the main Instance. In Non-Storing Mode, the base topological information to be passed to the PCE, that is the knowledge of the main DODAG, is already available at the Root. This specification introduces protocol extensions that enrich the topological information available to the Root with sibling relationships that are usable but not leveraged to form the main DODAG.

Based on usage, path length, and knowledge of available resources such as battery levels and reservable buffers in the nodes, the PCE with a global visibility of the system can optimize the computed routes for the application needs, including the capability to provide path redundancy. This specification also introduces protocol extensions that enable the Root to translate the computed paths into RPL and install them as Projected Routes (aka P-Routes) inside the DODAG on behalf of a PCE.

A P-Route may be installed in either Storing and Non-Storing Mode, potentially resulting in hybrid situations where the Mode in which the P-Route operates is different from that of the RPL main Instance. P-Routes can be used as stand-alone Segments meant to reduce the size of the source routing headers, leveraging loose source routing operations down the main RPL DODAG. P-Routes can also be combined with other P-Routes to form a protection Path called a Track and signaled as a RPL Instance. A Track provides underlay shortcuts in an existing main Instance, each with its own RIB.

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, the terms "Extends" and "Amends" are used as per [I-D.kuehlewind-update-tag] section 3.

2.2. References

In this document, readers will encounter terms and concepts that are discussed in the "Routing Protocol for Low Power and Lossy Networks" [RPL], the "6TiSCH Architecture" [RFC9030], the "Deterministic Networking Architecture" [RFC8655], the "Using RPI Option Type, Routing Header for Source Routes, and IPv6-in-IPv6 Encapsulation in the RPL Data Plane" [RFC9008], the "Reliable and Available Wireless (RAW) Architecture" [RAW-ARCHI], and "Terminology in Low power And Lossy Networks" [RFC7102]. Both architecture documents define the concept of Track in a compatible fashion. This documents only builds Tracks that are DODAGs, meaning that all links are oriented From Ingress to Egress. This specification also utilizes the terms Segment and Lane that are also defined in the RAW Architecture.

As opposed to routing trees, RPL DODAGs are typically constructed to provide redundancy and dynamically adapt the forwarding operation to the state of the LLN links. Note that the plain forwarding operation over DODAGs does not provide redundancy for all nodes, since at least the node nearest to the Root does not have an alternate feasible successor.

RAW solves that problem by defining Protection Paths that can be fully non-congruent and can be activated dynamically upon failures. This requires additional control to take the routing decision early enough along the Track to route around the failure.

RAW only uses single-ended DODAGs, meaning that they can be reversed in another DODAG by reversing all the links. The Ingress of the Track is the Root of the DODAG, whereas the Egress is the Root of the reversed DODAG. From the RAW perspective, single-ended DODAGs are special Tracks that only have forward links, and that can be leveraged to provide Protection services by defining destination-oriented Protection Paths within the DODAG.

2.3. Glossary

This document often uses the following acronyms:

ARQ: Automatic Repeat Request, in other words retries
FEC: Forward Error Correction
HARQ: Hybrid Automatic Repeat Request, combining FEC and ARQ
CMO: Control Message Option
DAO: Destination Advertisement Object
DAG: Directed Acyclic Graph
DODAG: Destination-Oriented Directed Acyclic Graph; A DAG with only one vertex (i.e., node) that has no outgoing edge (i.e., link)
GUA: IPv6 Global Unicast Address
LLN: Low-Power and Lossy Network
MOP: RPL Mode of Operation
P-DAO: Projected DAO
P-Route: Projected Route
PDR: P-DAO Request
PCE: Path Computation Element
PLR: Point of Local Repair
RAN: RPL-Aware Node (either a RPL router or a RPL-Aware Leaf)
RAL: RPL-Aware Leaf
RH: Routing Header
RIB: Routing Information Base, aka the routing table.
RPI: RPL Packet Information
RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks
RTO: RPL Target Option
RUL: RPL-Unaware Leaf
SIO: RPL Sibling Information Option
ULA: IPv6 Unique Local Address
NSM-VIO: A Source-Routed Via Information Option, used in Non-Storing Mode P-DAO messages
SLO: Service Level Objective
TIO: RPL Transit Information Option
SM-VIO: A strict Via Information Option, used in Storing Mode P-DAO messages
VIO: A Via Information Option; it can be an SM-VIO or a NSM-VIO

2.4. Domain Terms

This specification uses the following terminology:

2.4.1. Projected Route

A RPL P-Route is a RPL route that is computed remotely by a PCE, and installed and maintained by a RPL Root on behalf of the PCE. It is installed as a state that signals that destinations (aka Targets) are reachable along a sequence of nodes.

2.4.2. Projected DAO

A DAO message used to install a P-Route.

2.4.3. Path

Quoting section 1.1.3 of [INT-ARCHI]:

> At a given moment, all the IP datagrams from a particular source host to a particular destination host will typically traverse the same sequence of gateways. We use the term "path" for this sequence. Note that a path is uni-directional; it is not unusual to have different paths in the two directions between a given host pair.

Section 2 of [I-D.irtf-panrg-path-properties] points to a longer, more modern definition of path, which begins as follows:

> A sequence of adjacent path elements over which a packet can be transmitted, starting and ending with a node. A path is unidirectional. Paths are time-dependent, i.e., the sequence of path elements over which packets are sent from one node to another may change. A path is defined between two nodes.

It follows that the general acceptance of a path is a linear sequence of nodes, as opposed to a multi-dimensional graph. In the context of this document, a path is observed by following one copy of a packet that is injected in a Track and possibly replicated within.

2.4.4. Routing Stretch

RPL is anisotropic, meaning that it is directional, or more exactly polar. RPL does not behave the same way "downwards" (root towards leaves) with _multicast_ DIO messages that form the DODAG and "upwards" (leaves towards root) with _unicast_ DAO messages that follow the DODAG. This is in contrast with traditional IGPs that operate the same way in all directions and are thus called isotropic.

The term Routing Stretch denotes the length of a path, in comparison to the length of the shortest path, which can be an abstract concept in RPL when the metrics are statistical and dynamic, and the concept of distance varies with the Objective Function.

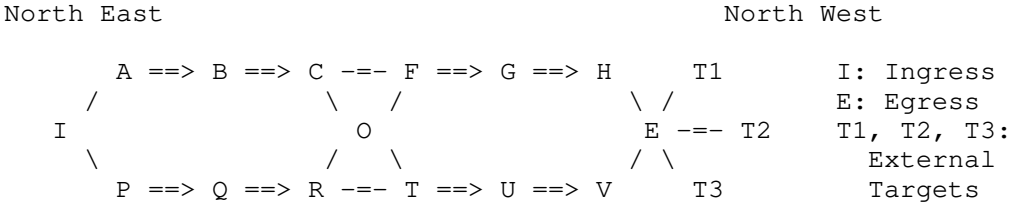
The RPL DODAG optimizes the P2MP (Point-to-MultiPoint) (from the Root) and MP2P (MultiPoint-to-Point) (towards the Root) paths, but the P2P (Point-to-Point) traffic has to follow the same DODAG. Following the DODAG, the RPL datapath passes via a common parent in Storing Mode and via the Root in Non-Storing Mode. This typically

involves more hops and more latency than the minimum possible for a direct P2P path that an isotropic protocol would compute. We refer to this elongated path as stretched.

2.4.5. Track

The concept of Track is inherited from the "6TiSCH Architecture" [RFC9030] and matches that of a Protection Path in the RAW Architecture" [RAW-ARCHI]. A Track is a networking graph that can be followed to transport packets with equivalent treatment; as opposed to the definition of a path above, a Track is not necessarily linear. It may contain multiple paths that may fork and rejoin, and may enable the RAW Packet ARQ, Replication, Elimination, and Overhearing (PAREO) operations.

Figure 1 illustrates the mapping of the DODAG with the generic concept of a Track, with the DODAG Root acting as Ingress for the Track, and the mapping of Lanes and Segments, and only forward Segments, meaning that they are directional and progressing towards the destination.



I ==> A ==> B ==> C : a Segment to targets F and O

I --> F --> E : a Lane to targets T1, T2, T3

I, A, B, C, F, G, H, E : a path to T1, T2, T3

Figure 1: A Track and its Components

This specification builds Tracks that are DODAGs oriented towards a Track Ingress, and the forward direction for packets (aka forward) is from the Track Ingress to one of the possibly multiple Track Egress Nodes, which is also down the DODAG.

The Track may be strictly connected, meaning that the vertices are adjacent, or loosely connected, meaning that the vertices are connected using Segments that are associated to the same Track.

2.4.5.1. TrackID

A RPL InstanceID (typically of a Local Instance) that identifies a Track using the namespace owned by the Track Ingress. For Local Instances, the TrackID is associated with the IPv6 Address of the Track Ingress that is used as DODAGID, and together they form a unique identification of the Track (see the definition of DODAGID in section 2 of [RPL].

2.4.5.2. Namespace

The term namespace is used to refer to the scope of the TrackID. The TrackID is locally significant within its namespace. For Local Instances, the namespace is identified by the DODAGID for the Track and the tuple (DODAGID, TrackID) is globally unique. For Global Instances, the namespace is the whole RPL domain.

2.4.5.3. Complex Track

A Track that can be traversed via more than one path (e.g., a DODAG).

2.4.5.4. Stand-Alone

Refers to a Segment or a Lane that is installed with a single P-DAO that fully defines the path, e.g., a stand-alone segment is installed with a single Storing Mode Via Information option (SM-VIO) all the way between Ingress and Egress.

2.4.5.5. Stitching

This specification uses the term stitching to indicate that a track is piped to another one, meaning that traffic out of the first track is injected into the other track.

2.4.5.6. Lane

The concept of Lane is defined in the RAW Architecture" [RAW-ARCHI] as an end-to-end forward serial path. With this specification, a Lane is installed by the Root of the main DODAG using a Non-Storing Mode P-DAO message, e.g., I --> F --> E in Figure 1.

As the Non-Storing Mode Via Information option (NSM-VIO) can only signal sequences of nodes, it takes one Non-Storing Mode P-DAO message per Lane to signal the structure of a complex Track.

Each NSM-VIO for the same TrackId but with a different Segment ID signals a different Lane that the Track Ingress adds to the topology.

2.4.5.7. Segment

A serial path formed by a strict sequence of nodes, along which a P-Route is installed, e.g., I ==> A ==> B ==> C in Figure 1. With this specification, a Segment is typically installed by the Root of the main DODAG using Storing Mode P-DAO messages. A Segment is used as the topological edge of a Track joining the loose steps along the Lanes that form the structure of a complex Track. The same Segment may be leveraged by more than one Lane where the Lanes overlap.

Since this specification builds only DODAGs, all Segments are oriented from Ingress (East) to Egress (West), as opposed to the general Track model in the RAW Architecture [RAW-ARCHI], which allows North/South Segments that can be bidirectional as well.

2.4.5.7.1. Section of a Segment

A continuous subset of a Segment that may be replaced while the Segment remains. For instance, in Segment A=>B=>C=>D=>E=>F, say that the link C to D might be misbehaving. The section B=>C=>D=>E in the Segment may be replaced by B=>C=>D=>E to route around the problem. The Segment becomes A=>B=>C=>D=>E=>F.

2.4.5.7.2. Segment Routing and SRH

The terms Segment Routing and SRH refer to using source-routing to hop over Segments. In a Non-Storing mode RPL domain, the SRH is typically a RPL Source Route Header (the IPv6 RH of type 3) as defined in [RFC6554].

If the network is a 6LoWPAN Network, the expectation is that the SRH is compressed and encoded as a 6LoWPAN Routing Header (6LoRH), as specified in section 5 of [RFC8138].

On the other hand, if the RPL Network is less constrained and operated in Storing Mode, as discussed in Section 7.1, the Segment Routing operation and the SRH could be as specified in [RFC8754]. This specification applies equally to both forms of source routing and SRH.

3. Context and Goal

3.1. RPL Applicability

RPL is optimized for situations where the power is scarce, the bandwidth is constrained and the transmissions are unreliable. This matches the use case of an IoT LLN where RPL is typically used today, but also situations of high relative mobility between the nodes in the network (aka swarming), e.g., within a variable set of vehicles with a similar global motion, or a platoon of drones.

To reach this goal, RPL is primarily designed to minimize the control plane activity, that is the relative amount of routing protocol exchanges vs. data traffic, and the amount of state that is maintained in each node. RPL does not need to converge, and provides connectivity to most nodes most of the time.

RPL may form multiple topologies called instances. Instances can be created to enforce various optimizations through objective functions, or to reach out through different Root Nodes. The concept of objective function allows to adapt the activity of the routing protocol to the use case, e.g., type, speed, and quality of the LLN links.

RPL instances operate as ships passing in the night, unbeknownst of one another. The RPL Root is responsible for selecting the RPL Instance that is used to forward a packet coming from the Backbone into the RPL domain and for setting the related RPL information in the packets. Each Instance creates its own routing table (RIB) in participating nodes, and the RIB associated to the instance must be used end to end in the RPL domain. To that effect, RPL tags the packets with the Instance ID in a Hop-by-Hop extension Header. 6TiSCH leverages RPL for its distributed routing operations.

To reduce the routing exchanges, RPL leverages an anisotropic Distance Vector approach, which does not need a global knowledge of the topology, and only optimizes the routes to and from the RPL Root, allowing P2P paths to be stretched. Although RPL installs its routes proactively, it only maintains them lazily, in reaction to actual traffic, or as a slow background activity.

This is simple and efficient in situations where the traffic is mostly directed from or to a central node, such as the control traffic between routers and a controller of a Software Defined Networking (SDN) infrastructure or an Autonomic Control Plane (ACP).

But stretch in P2P routing is counter-productive to both reliability and latency as it introduces additional delay and chances of loss. As a result, [RPL] is not a good fit for the use cases listed in the RAW use cases document [RFC9450], which demand high availability and reliability, and as a consequence require both short and diverse paths.

3.2. Multi-Topology Routing and Loop Avoidance

RPL first forms a default route in each node towards the Root, and those routes together coalesce as a Directed Acyclic Graph oriented upwards. RPL then constructs routes to destinations signaled as Targets in the reverse direction, down the same DODAG. To do so, a RPL Instance can be operated either in RPL Storing or Non-Storing Mode of Operation (MOP). The default route towards the Root is maintained aggressively and may change while a packet progresses without causing loops, so the packet will still reach the Root.

In Non-Storing Mode, each node advertises itself as a Target directly to the Root, indicating the parents that may be used to reach itself. Recursively, the Root builds and maintains an image of the whole DODAG in memory, and leverages that abstraction to compute source route paths for the packets to their destinations down the DODAG. When a node changes its point(s) of attachment to the DODAG, it takes a single unicast packet to the Root along the default route to update it, and the connectivity to the node is restored immediately; this mode is preferable for use cases where internet connectivity is dominant, or when the Root controls the network activity in the nodes, which is the case of this draft.

In Storing Mode, the routing information percolates upwards, and each node maintains the routes to the subDAG of its descendants down the DODAG. The maintenance is lazy, either reactive upon traffic or as a slow background process. Packets flow via the common parent and the routing stretch is reduced compared to Non-Storing MOP, for better P2P connectivity. However, a new route takes a longer time to propagate to the Root, since it takes time for the Distance-Vector protocol to operate hop-by-hop, and the connectivity from the internet to the node is restored more slowly upon node movement.

Either way, the RPL routes are injected by the Target nodes, in a distributed fashion. To complement RPL and eliminate routing stretch, this specification introduces a hybrid mode that combines Storing and Non-Storing operations to build and project routes onto the nodes where they should be installed. This specification uses the term Projected Route (P-Route) to refer to those routes.

In the simplest mode of this specification, Storing-Mode P-Routes can be deployed to join the dots of a loose source routing header (SRH) in the main DODAG. In that case, all the routes (source routed and P-Routes) belong to the Routing Information base (RIB) associated with the main Instance. Storing-Mode P-Routes are referred to as Segments in this specification.

A set of P-Routes can also be projected to form a dotted-line underlay of the main Instance and provide Traffic Engineered paths for an application. In that case, the P-Routes are installed in Non-Storing Mode and the set of P-Routes is called a Track. A Track is associated with its own RPL Instance, and, as any RPL Instance, with its own Routing Information base (RIB). As a result, each Track defines a routing topology in the RPL domain. As for the main DODAG, Segments associated to the Track Instance may be deployed to join the dots using Storing-Mode P-Routes.

Routing in a multi-topology domain may cause loops unless strict rules are applied. This specification defines two strict orders to ensure loop avoidance when projected routes are used in a RPL domain, one between forwarding methods and one between RPL Instances, seen as routing topologies.

The first and strict order relates to the forwarding method and the more specifically the origin of the information used in the next-hop computation. The possible forwarding methods are: 1) to a direct next hop, 2) to an indirect neighbor via a common neighbor, 3) along a Segment, and 4) along a nested Track. The methods are strictly ordered as listed above, more in Section 6.7. A forwarding method may leverage any of the lower order ones, but never one with a higher order; for instance, when forwarding a packet along a Segment, the router may use direct or indirect neighbors but cannot use a Track. The lower order methods have a strict precedence, so the router will always prefer a direct neighbor over an indirect one, or a Segment within the current RPL Instance vs. another Track.

The second strict and partial order is between RPL Instances. It allows the RPL node to detect an error in the state installed by the PCE, e.g., after a desynchronization. That order must be defined by the administrator for his RPL domain and defines a DODAG of underlays with the main Instance as Root. The relation of RPL instances may be represented as a DODAG of instances where the main instance is Root. The rule is that a RPL Instance may leverage another RPL instance as underlay if and only if that other Instance is one of its descendants in the graph. Supporting this method is OPTIONAL for nested Tracks and REQUIRED between a Track instance and the main instance. It may be done using network management, or future extensions to this specifications. When it is not communicated, then the RPL nodes

consider by default that all Track instances are children of the main instance, and do not attempt to validate the order for nested Tracks, trusting the PCE implicitly. As a result, a packet that is being forwarded along the main Instance may be encapsulated in any Track, but a packet that was forwarded along a Track MUST NOT be forwarded along the default route of main Instance.

3.3. Requirements

3.3.1. Loose Source Routing

A RPL implementation operating in a very constrained LLN typically uses the Non-Storing Mode of Operation as represented in Figure 2. In that mode, a RPL node indicates a parent-child relationship to the Root, using a destination Advertisement Object (DAO) that is unicast from the node directly to the Root, and the Root typically builds a source routed path to a destination down the DODAG by recursively concatenating this information.

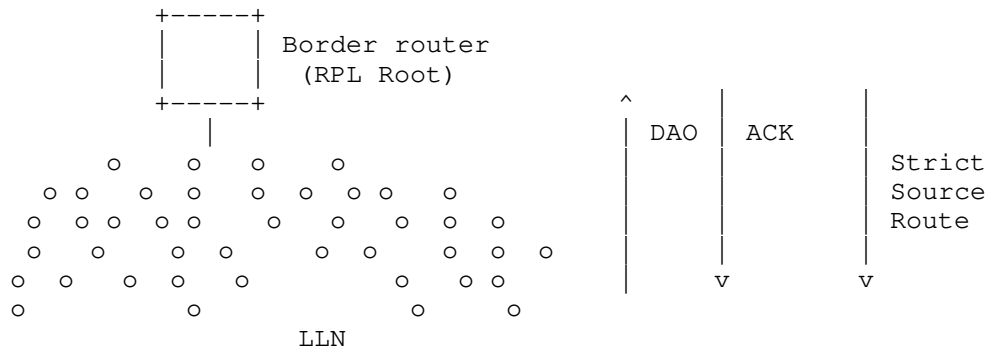


Figure 2: RPL Non-Storing Mode of operation

Based on the parent-children relationships expressed in the Non-Storing DAO messages, the Root possesses topological information about the whole network, though this information is limited to the structure of the DODAG for which it is the destination. A packet that is generated within the domain will always reach the Root, which can then apply a source routing information to reach the destination if the destination is also in the DODAG. Similarly, a packet coming from the outside of the domain for a destination that is expected to be in a RPL domain reaches the Root. This results in the wireless bandwidth near the Root being the limiting factor for all transmissions towards or within the domain, and that the Root is a single point of failure for all connectivity to nodes within its domain.

The RPL Root must add a source routing header to all downward packets. As a network grows, the size of the source routing header increases with the depth of the network. In some use cases, a RPL network forms long lines along physical structures such as streets for lighting. Limiting the packet size is beneficial to the energy budget, directly for the current transmission, but also indirectly since it reduces the chances of frame loss and energy spent in retries, e.g., by ARQ over one hop at Layer-2, or end-to-end at upper layers. Using smaller packets also reduces the chances of packet fragmentation, which is highly detrimental to the LLN operation, in particular when fragments are forwarded but not recovered, see [RFC8930] vs. [RFC8931] for more.

A limited amount of well-targeted routing state would allow the source routing operation to be loose as opposed to strict, and reduce the overhead of routing information in packets. Because the capability to store routing state in every node is limited, the decision of which route is installed where can only be optimized with global knowledge of the system, knowledge that the Root or an associated PCE may possess by means that are outside the scope of this specification.

Being on-path for all packets in Non-Storing mode, the Root may determine the number of P2P packets in its RPL domain per source and destination, the latency incurred, and the amount of energy and bandwidth that is consumed to reach itself and then back down, including possible fragmentation when encapsulating larger packets. Enabling a shorter path that would not traverse the Root for select P2P source/destinations may improve the latency, lower the consumption of constrained resources, free bandwidth at the bottleneck near the Root, improve the delivery ratio and reduce the latency for those P2P flows with a global benefit for all flows by reducing the load at the Root.

To limit the need for source route headers in deep networks, one possibility is to store a routing state associated with the main DODAG in select RPL routers down the path. The Root may elide the sequence of routers that is installed in the network from its source route header, which therefore becomes loose, in contrast to being strict in [RPL].

3.3.2. forward Routes

[RPL] optimizes Point-to-Multipoint (P2MP) routes from the Root, Multipoint-to-Point (MP2P) routes to the DODAG Root, and Internet access when the Root also serves as Border Router. All routes are installed North-South (aka up/down) along the RPL DODAG. Peer to Peer (P2P) forward routes in a RPL network will generally experience elongated (stretched) paths versus direct (optimized) paths, since routing between two nodes always happens via a common parent, as illustrated in Figure 3:

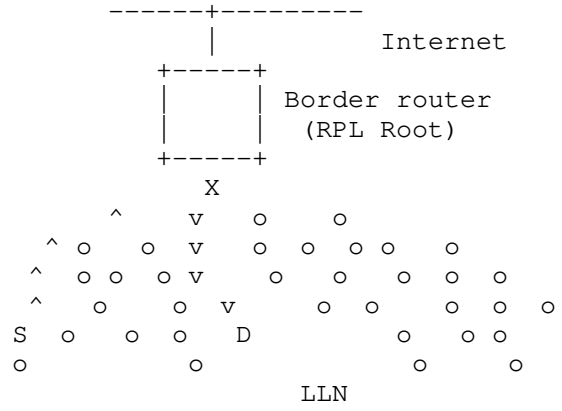


Figure 3: Routing Stretch between S and D via common parent X along North-South Paths

As described in [RFC9008], the amount of stretch depends on the Mode of Operation:

* in Non-Storing Mode, all packets routed within the DODAG flow all the way up to the Root of the DODAG. If the destination is in the same DODAG, the Root must encapsulate the packet to place an RH that has the strict source route information down the DODAG to the destination. This will be the case even if the destination is relatively close to the source and the Root is relatively far off.

* In Storing Mode, unless the destination is a child of the source, the packets will follow the default route up the DODAG as well. If the destination is in the same DODAG, they will eventually reach a common parent that has a route to the destination; at worse, the common parent may also be the Root. From that common parent, the packet will follow a path down the DODAG that is optimized for the Objective Function that was used to build the DODAG.

It turns out that it is often beneficial to enable forward P2P routes, either if the RPL route presents a stretch from the shortest path, or if the new route is engineered with a different objective, and this is even more critical in Non-Storing Mode than it is in Storing Mode, because the routing stretch is wider. For that reason, earlier work at the IETF introduced the "Reactive Discovery of Point-to-Point Routes in Low Power and Lossy Networks" [RFC6997], which specifies a distributed method for establishing optimized P2P routes. This draft proposes an alternative based on centralized route computation.

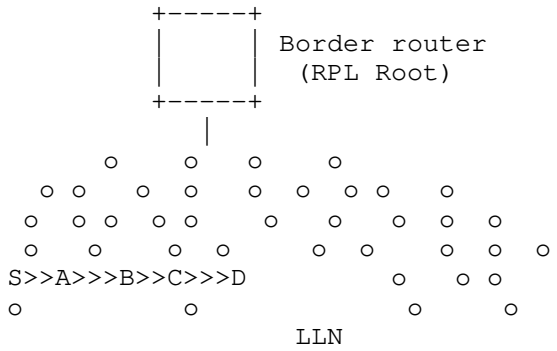


Figure 4: More direct forward Route between S and D

The requirement is to install additional routes in the RPL routers, to reduce the stretch of some P2P routes and maintain the characteristics within a given SLO, e.g., in terms of latency and/or reliability.

3.4. On Tracks

3.4.1. Building Tracks With RPL

The concept of a Track was introduced in the "6TiSCH Architecture" [RFC9030], as a collection of potential paths that leverage redundant forwarding solutions along the way. This can be a DODAG or a more complex structure that is only partially acyclic (e.g., per packet).

With this specification, a Track is shaped as a DODAG, and following the directed edges leads to a Track Ingress. Storing Mode P-DAO messages follow the direction of the edges to set up routes for traffic that flows the other way, towards the Track Egress(es). If there is a single Track Egress, then the Track is reversible to form another DODAG by reversing the direction of each edge. A node at the Ingress of more than one Segment in a Track may use one or more of these Segments to forward a packet inside the Track.

A RPL Track is a collection of (one or more) parallel loose source routed sequences of nodes ordered from Ingress to Egress, each forming a lane. The nodes that are directly connected, reachable via existing Tracks as illustrated in Section 3.5.2.3 or joined with strict Segments of other nodes as shown in Section 3.5.1.3. The Lanes are expressed in RPL Non-Storing Mode and require an encapsulation to add a Source Route Header, whereas the Segments are expressed in RPL Storing Mode.

A path provides only one path between Ingress and Egress. It comprises at most one Lane. A Stand-Alone Segment implicitly defines a path from its Ingress to Egress.

A complex Track forms a graph that provides a collection of potential paths to provide redundancy for the packets, either as a collection of Lanes that may be parallel or cross at certain points, or as a more generic DODAG.

3.4.2. Tracks and RPL Instances

Section 5.1. of [RPL] describes the RPL Instance and its encoding. There can be up to 128 Global RPL Instances, for which there can be one or more DODAGs, and there can be 64 local RPL Instances, with a namespace that is indexed by a DODAGID, where the DODAGID is a Unique Local Address (ULA) or a Global Unicast Address (GUA) of the Root of the DODAG. Bit 0 (most significant) is set to 1 to signal a Local RPLInstanceID, as shown in Figure 5. By extension, this specification expresses the value of the RPLInstanceID as a single integer between 128 and 191, representing both the Local RPLInstanceID in 0..63 in the rightmost bits and Bit 0 set.

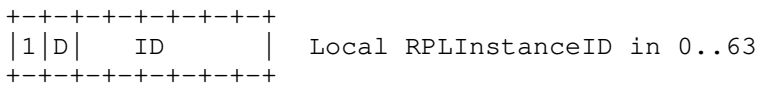


Figure 5: Local RPLInstanceID Encoding

A Track typically forms an underlay to the main Instance, and is associated with a Local RPL Instance from which the RPLInstanceID is used as the TrackID. When a packet is placed on a Track, it is encapsulated IP-in-IP with a RPL Option containing a RPI which signals the RPLInstanceID. The encapsulating source IP address and RPI Instance are set to the Track Ingress IP address and local RPLInstanceID, respectively, more in Section 6.3.

A Track typically offers service protection across several lanes. As a degraded form of a Track, a path made of a single lane (i.e., offering no protection) can be used as an alternative to a Segment for forwarding along a RPL Instance. In that case, instead of following native routes along the instance, the packets are encapsulated to signal a more specific source-routed path between the loose hops in the encapsulated source routing header.

If the encapsulated packet follows a global instance, then the lane may be part that global instance as well, for instance the global instance of the main DODAG. This can only be done for global instances because the Ingress node that encapsulates the packets over the lane is not the Root of the instance, so the source address of the encapsulated packet cannot be used to determine the Track along the way.

3.5. path Signaling

This specification enables setting up a P-Route along either a lane or a Segment. A P-Route is installed and maintained by the Root of the main DODAG using an extended RPL DAO message called a Projected DAO (P-DAO), and a Track is composed of the combination of one or more P-Routes. In order to clarify the techniques that may be used to install a P-Route, this section takes the simple case of the path illustrated in Figure 6. So the goal is to build a path from node A to E for packets towards E's neighbors F and G along A, B, C, D and E as opposed to via the Root:

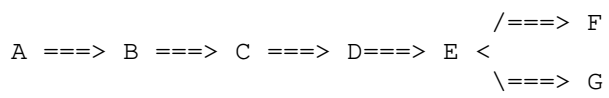


Figure 6: Reference Track

A P-DAO message for a Track signals the TrackID in the RPLInstanceID field. In the case of a local RPL Instance, the address of the Track Ingress is used as source to encapsulate packets along the Track. The Track is signaled in the DODAGID field of the Projected DAO Base Object, see Figure 8.

This specification introduces the Via Information Option (VIO) to signal a sequence of hops in a Lane or a Segment in the P-DAO messages, either in Storing Mode (SM-VIO) or Non-Storing Mode (NSM-VIO). One P-DAO message contains a single VIO, associated to one or more RPL Target Options that signal the destination IPv6 addresses that can reached along the Track (more in Section 5.3).

Before diving deeper into Track Lanes and Segments signaling and operation, this section provides examples of how route projection works through variations of a simple example. This simple example illustrates the case of host routes, though RPL Targets can also be prefixes.

Conventionally we use ==> to represent a strict hop and --> for a loose hop. We use "-to-", such as in C==>D==>E-to-F to represent coma-separated Targets, e.g., F is a Target for Segment C==>D==>E. In this example, A is the Track Ingress and E is the Track Egress. C is a stitching point. F and G are "external Targets for the Track, and become reachable from A via the Track A (Ingress) to E (Egress and implicit Target in Non-Storing Mode) leading to F and G (explicit Targets).

In a general manner the desired outcome is as follows:

* Targets are E, F, and G

* P-DAO 1 signals C==>D==>E

* P-DAO 2 signals A==>B==>C

* P-DAO 3 signals F and G via the A-->E Track

P-DAO 3 may be ommitted if P-DAO 1 and 2 signal F and G as Targets.

Loose sequences of hops are expressed in Non-Storing Mode; this is why P-DAO 3 contains a NSM-VIO. With this specification:

* the DODAGID to be used by the Ingress as source address is signaled in the DAO base object (see Figure 8) .

* the via list in the VIO is encoded as an SRH-6LoRH (see Figure 16), and it starts with the address of the first hop node after the Ingress node in the loose hop sequence.

* the via list ends with the address of the Egress node.

Note well:

> The Egress of a Non-Storing Mode P-Route is implicitly a target; it is not listed in the RPL Target Options but still accounted for as if it was. The only exception is when the Egress is the only address listed in the VIO, in which case it would indicate via itself which would be non-sensical.

Also:

> By design, the list of nodes in a VIO in Non-Storing Mode is exactly the list that shows in the encapsulation SRH. So in the cases detailed below, if the Mode of the P-DAO is Non-Storing, then the VIO row can be read as indicating the SRH as well.

3.5.1. Using Storing Mode Segments

A==>B==>C and C==>D==>E are Segments of the same Track. Note that the Storing Mode signaling imposes strict continuity in a Segment, since the P-DAO is passed hop by hop, as a classical DAO is, along the reverse datapath that it signals. One benefit of strict routing is that loops are avoided along the Track.

3.5.1.1. Stitched Segments

In this formulation:

* P-DAO 1 signals C==>D==>E-to-F,G

* P-DAO 2 signals A==>B==>C-to-F,G

Storing Mode P-DAO 1 is sent to E and when it is successfully acknowledged, Storing Mode P-DAO 2 is sent to C, as follows:

Field	P-DAO 1 to E	P-DAO 2 to C
Mode	Storing	Storing
Track Ingress	A	A
(DODAGID, TrackID)	(A, 129)	(A, 129)
SegmentID	1	2
VIO	C, D, E	A, B, C
Targets	F, G	F, G

Table 1: P-DAO Messages

As a result the RIBs are set as follows:

Node	Destination	Origin	Next Hop(s)	TrackID
E	F, G	P-DAO 1	Neighbor	(A, 129)
D	E	P-DAO 1	Neighbor	(A, 129)
"	F, G	P-DAO 1	E	(A, 129)
C	D	P-DAO 1	Neighbor	(A, 129)
"	F, G	P-DAO 1	D	(A, 129)
B	C	P-DAO 2	Neighbor	(A, 129)
"	F, G	P-DAO 2	C	(A, 129)
A	B	P-DAO 2	Neighbor	(A, 129)
"	F, G	P-DAO 2	B	(A, 129)

Table 2: RIB setting

Note:

| the " sign is used throughout those tables to indicate the same value as in the row above.

Packets originating at A going to F or G do not require encapsulation as the RPI can be placed in the native header chain. For packets that it routes, A must encapsulate to add the RPI that signals the trackID; the outer headers of the packets that are forwarded along the Track have the following settings:

Header	IPv6 Source Addr.	IPv6 Dest. Addr.	TrackID in RPI
Outer	A	F or G	(A, 129)
Inner	Any but A	F or G	N/A

Table 3: Packet Header Settings

As an example, say that A has a packet for F. Using the RIB above:

* From P-DAO 2: A forwards to B and B forwards to C.

* From P-DAO 1: C forwards to D and D forwards to E.

* From Neighbor Cache Entry: E delivers the packet to F.

3.5.1.2. External Routes

In this example, we consider F and G as destinations that are external to the Track as a DODAG, as discussed in section 4.1.1. of [RFC9008]. We then apply the directives for encapsulating in that case (more in Section 6.7).

In this formulation, we set up the lane explicitly, which creates less routing state in intermediate hops at the expense of larger packets to accommodate source routing:

* P-DAO 1 signals C==>D==>E-to-E

* P-DAO 2 signals A==>B==>C-to-E

* P-DAO 3 signals F and G via the A-->E-to-F,G Track

Storing Mode P-DAO 1 and 2, and Non-Storing Mode P-DAO 3, are sent to E, C and A, respectively, as follows:

	P-DAO 1 to E	P-DAO 2 to C	P-DAO 3 to A
Mode	Storing	Storing	Non-Storing
Track Ingress	A	A	A
(DODAGID, TrackID)	(A, 129)	(A, 129)	(A, 129)
SegmentID	1	2	3
VIO	C, D, E	A, B, C	E
Targets	E	E	F, G

Table 4: P-DAO Messages

Note in the above that E is not an implicit Target in Storing mode, so it must be added in the RTO for P-DAO 1 and 2. E is not an implicit Target for P-DAO 3 either, since E is the only entry in the VIO.

As a result the RIBs are set as follows:

Node	Destination	Origin	Next Hop(s)	TrackID
E	F, G	P-DAO 1	Neighbor	(A, 129)
D	E	P-DAO 1	Neighbor	(A, 129)
C	D	P-DAO 1	Neighbor	(A, 129)
"	E	P-DAO 1	D	(A, 129)
B	C	P-DAO 2	Neighbor	(A, 129)
"	E	P-DAO 2	C	(A, 129)
A	B	P-DAO 2	Neighbor	(A, 129)
"	E	P-DAO 2	B	(A, 129)
"	F, G	P-DAO 3	E	(A, 129)

Table 5: RIB setting

Packets from A to E do not require an encapsulation. This is why in the tables below, E may show as IPv6 Destination Address only if the IPv6 Source Address X is different from A. Conversely, the encapsulation is always done when the IPv6 Destination Address is F or G. Other destination addresses do not match this P-Route and are not subject to encapsulation.

The outer headers of the packets that are forwarded along the Track have the following settings:

Header	IPv6 Source Addr.	IPv6 Dest. Addr.	TrackID in RPI
Outer	A	E	(A, 129)
Inner	X	either E if(X!=A), or F, or G	N/A

Table 6: Packet Header Settings

As an example, say that A has a packet for F. Using the RIB above:

* From P-DAO 3: A encapsulates the packet and sends it down the Track signaled by P-DAO 3, with the outer header above. Now the packet destination is E.

* From P-DAO 2: A forwards to B and B forwards to C.

* From P-DAO 1: C forwards to D and D forwards to E; E decapsulates the packet.

* From Neighbor Cache Entry: E delivers packets to F or G.

3.5.1.3. Segment Routing

In this formulation Track Lanes are leveraged to combine Segments and form a Graph. The packets are source routed from a Segment to the next to adapt the path. As such, this can be seen as a form of Segment Routing [RFC8402]:

* P-DAO 1 signals C==>D==>E-to-E

* P-DAO 2 signals A==>B-to-B,C

* P-DAO 3 signals F and G via the A-->C-->E-to-(E),F,G Track

Storing Mode P-DAO 1 and 2, and Non-Storing Mode P-DAO 3, are sent to E, B and A, respectively, as follows:

	P-DAO 1 to E	P-DAO 2 to B	P-DAO 3 to A
Mode	Storing	Storing	Non-Storing
Track Ingress	A	A	A
(DODAGID, TrackID)	(A, 129)	(A, 129)	(A, 129)
SegmentID	1	2	3
VIO	C, D, E	A, B	C, E
Targets	E	B, C	F, G

Table 7: P-DAO Messages

Note in the above that the Segment can terminate at the loose hop as used in the example of P-DAO 1 or at the previous hop as done with P-DAO 2. Both methods are possible on any Segment joined by a loose

lane. P-DAO 1 generates more signaling since E is the Segment Egress when D could be, but has the benefit that it validates that the connectivity between D and E still exists.

As a result the RIBs are set as follows:

Node	Destination	Origin	Next Hop(s)	TrackID
E	F, G	P-DAO 1	Neighbor	(A, 129)
D	E	P-DAO 1	Neighbor	(A, 129)
C	D	P-DAO 1	Neighbor	(A, 129)
"	E	P-DAO 1	D	(A, 129)
B	C	P-DAO 2	Neighbor	(A, 129)
A	B	P-DAO 2	Neighbor	(A, 129)
"	C	P-DAO 2	B	(A, 129)
"	E, F, G	P-DAO 3	C, E	(A, 129)

Table 8: RIB setting

Packets originated at A to E do not require an encapsulation, but carry a SRH via C. The outer headers of the packets that are forwarded along the Track have the following settings:

Header	IPv6 Source Addr.	IPv6 Dest. Addr.	TrackID in RPI
Outer	A	C until C then E	(A, 129)
Inner	X	either E if(X!=A), or F, or G	N/A

Table 9: Packet Header Settings

As an example, say that A has a packet for F. Using the RIB above:

* From P-DAO 3: A encapsulates the packet the Track signaled by P-DAO 3, with the outer header above. Now the destination in the IPv6 Header is C, and a SRH signals the final destination is E.

* From P-DAO 2: A forwards to B and B forwards to C.

* From P-DAO 3: C processes the SRH and sets the destination in the IPv6 Header to E.

* From P-DAO 1: C forwards to D and D forwards to E; E decapsulates the packet.

* From the Neighbor Cache Entry: E delivers packets to F or G.

3.5.2. Using Non-Storing Mode joining Tracks

In this formulation:

* P-DAO 1 signals C==>D==>E-to-(E),F,G

* P-DAO 2 signals A==>B==>C-to-(C),E,F,G

A==>B==>C and C==>D==>E are Tracks expressed as Non-Storing P-DAOs.

3.5.2.1. Stitched Tracks

Non-Storing Mode P-DAO 1 and 2 are sent to C and A respectively, as follows:

	P-DAO 1 to C	P-DAO 2 to A
Mode	Non-Storing	Non-Storing
Track Ingress	C	A
(DODAGID, TrackID)	(C, 131)	(A, 131)
SegmentID	1	1
VIO	D, E	B, C
Targets	F, G	E, F, G

Table 10: P-DAO Messages

As a result the RIBs are set as follows (using ND to indicate that the address is discovered by IPv6 Neighbor Discovery [RFC4861][RFC8505] or an equivalent method:

Node	Destination	Origin	Next Hop(s)	TrackID
E	F, G	ND	Neighbor	Any
D	E	ND	Neighbor	Any
C	D	ND	Neighbor	Any
"	E, F, G	P-DAO 1	D, E	(C, 131)
B	C	ND	Neighbor	Any
A	B	ND	Neighbor	Any
"	C, E, F, G	P-DAO 2	B, C	(A, 131)

Table 11: RIB setting

Packets originated at A to E, F and G could be generated with the RPI and the SRH, and no encapsulation. Alternatively, A may generate a native packet to the target, and then encapsulate it with an RPI and an SRH indicating the source-routed path leading to E, as it would for a packet that it routes coming from another node. This is effectively the same case as for packets generated by the root in a RPL network in Non-Storing mode, see section 8.1.3 of [RFC9008]. The latter is often is preferred since it leads to a single code path, and the destination when it is F or G, does no understand and process the RPI or the SRH. Either way, they carry a SRH via B and C, and C needs to encapsulate to E, F, or G to add an SRH via D and E. The encapsulating headers of packets that are forwarded along the Track between C and E have the following settings:

Header	IPv6 Source Addr.	IPv6 Dest. Addr.	TrackID in RPI
Outer	C	D until D then E	(C, 131)
Inner	X	E, F, or G	N/A

Table 12: Packet Header Settings between C and E

As an example, say that A has a packet for F. Using the RIB above:

* From P-DAO 2: A encapsulates the packet with destination of F in the Track signaled by P-DAO 2. The outer header has source A, destination B, an SRH that indicates C as the next loose hop, and a RPI indicating a TrackId of 131 from A's namespace, which is distinct from TrackId of 131 from C's.

* From the SRH: Packets forwarded by B have source A, destination C, a consumed SRH, and a RPI indicating a TrackId of 131 from A's namespace. C decapsulates.

* From P-DAO 1: C encapsulates the packet with destination of F in the Track signaled by P-DAO 1. The outer header has source C, destination D, an SRH that indicates E as the next loose hop, and a RPI indicating a TrackId of 131 from C's namespace. E decapsulates.

3.5.2.2. External Routes

In this formulation:

* P-DAO 1 signals C==>D==>E-to-(E)

* P-DAO 2 signals A==>B==>C-to-(C),E

* P-DAO 3 signals F and G via the A-->E-to-F,G Track

Non-Storing Mode P-DAO 1 is sent to C and Non-Storing Mode P-DAO 2 and 3 are sent to A, as follows:

	P-DAO 1 to C	P-DAO 2 to A	P-DAO 3 to A
Mode	Non-Storing	Non-Storing	Non-Storing
Track Ingress	C	A	A
(DODAGID, TrackID)	(C, 131)	(A, 129)	(A, 141)
SegmentID	1	1	1
VIO	D, E	B, C	E
Targets		E	F, G

Table 13: P-DAO Messages

Note in the above that E is an implicit Target in P-DAO 1 and so is C in P-DAO 2. As Non-Storing Mode Egress nodes addresses, they not listed in the respective RTOs.

As a result the RIBs are set as follows:

Node	Destination	Origin	Next Hop(s)	TrackID
E	F, G	ND	Neighbor	Any
D	E	ND	Neighbor	Any
C	D	ND	Neighbor	Any
"	E	P-DAO 1	D, E	(C, 131)
B	C	ND	Neighbor	Any
A	B	ND	Neighbor	Any
"	C, E	P-DAO 2	B, C	(A, 129)
"	F, G	P-DAO 3	E	(A, 141)

Table 14: RIB setting

The encapsulating headers of packets that are forwarded along the Track between C and E have the following settings:

Header	IPv6 Source Addr.	IPv6 Dest. Addr.	TrackID in RPI
Outer	C	D until D then E	(C, 131)
Middle	A	E	(A, 141)
Inner	X	E, F or G	N/A

Table 15: Packet Header Settings

As an example, say that A has a packet for F. Using the RIB above:

* From P-DAO 3: A encapsulates the packet with destination of F in the Track signaled by P-DAO 3. The outer header has source A, destination E, and a RPI indicating a TrackId of 141 from A's namespace. This recurses with:

* From P-DAO 2: A encapsulates the packet with destination of E in the Track signaled by P-DAO 2. The outer header has source A, destination B, an SRH that indicates C as the next loose hop, and a RPI indicating a TrackId of 129 from A's namespace.

* From the SRH: Packets forwarded by B have source A, destination C , a consumed SRH, and a RPI indicating a TrackId of 129 from A's namespace. C decapsulates.

* From P-DAO 1: C encapsulates the packet with destination of E in the Track signaled by P-DAO 1. The outer header has source C, destination D, an SRH that indicates E as the next loose hop, and a RPI indicating a TrackId of 131 from C's namespace. E decapsulates.

3.5.2.3. Segment Routing

In this formulation:

* P-DAO 1 signals C==>D==>E-to-(E)

* P-DAO 2 signals A==>B-to-C

* P-DAO 3 signals F and G via the A-->C-->E-to-(E),F,G Track

Non-Storing Mode P-DAO 1 is sent to C and Non-Storing Mode P-DAO 2 and 3 are sent to A, as follows:

	P-DAO 1 to C	P-DAO 2 to A	P-DAO 3 to A
Mode	Non-Storing	Non-Storing	Non-Storing
Track Ingress	C	A	A
(DODAGID, TrackID)	(C, 131)	(A, 129)	(A, 141)
SegmentID	1	1	1
VIO	D, E	B	C, E
Targets		C	F, G

Table 16: P-DAO Messages

As a result the RIBs are set as follows:

Node	Destination	Origin	Next Hop(s)	TrackID
E	F, G	ND	Neighbor	Any
D	E	ND	Neighbor	Any
C	D	ND	Neighbor	Any
"	E	P-DAO 1	D, E	(C, 131)
B	C	ND	Neighbor	Any
A	B	ND	Neighbor	Any
"	B, C	P-DAO 2	C	(A, 129)
"	E, F, G	P-DAO 3	C, E	(A, 141)

Table 17: RIB setting

The encapsulating headers of packets that are forwarded along the Track between A and B have the following settings:

Header	IPv6 Source Addr.	IPv6 Dest. Addr.	TrackID in RPI
Outer	A	B until D then E	(A, 129)
Middle	A	C	(A, 141)
Inner	X	E, F or G	N/A

Table 18: Packet Header Settings

The encapsulating headers of packets that are forwarded along the Track between B and C have the following settings:

Header	IPv6 Source Addr.	IPv6 Dest. Addr.	TrackID in RPI
Outer	A	C	(A, 141)
Inner	X	E, F or G	N/A

Table 19: Packet Header Settings

The encapsulating headers of packets that are forwarded along the Track between C and E have the following settings:

Header	IPv6 Source Addr.	IPv6 Dest. Addr.	TrackID in RPI
Outer	C	D until D then E	(C, 131)
Middle	A	E	(A, 141)
Inner	X	E, F or G	N/A

Table 20: Packet Header Settings

As an example, say that A has a packet for F. Using the RIB above:

* From P-DAO 3: A encapsulates the packet with destination of F in the Track signaled by P-DAO 3. The outer header has source A, destination C, an SRH that indicates E as the next loose hop, and a RPI indicating a TrackId of 141 from A's namespace. This recurses with:

* From P-DAO 2: A encapsulates the packet with destination of C in the Track signaled by P-DAO 2. The outer header has source A, destination B, and a RPI indicating a TrackId of 129 from A's namespace. B decapsulates forwards to C based on a sibling connected route.

* From the SRH: C consumes the SRH and makes the destination E.

* From P-DAO 1: C encapsulates the packet with destination of E in the Track signaled by P-DAO 1. The outer header has source C, destination D, an SRH that indicates E as the next loose hop, and a RPI indicating a TrackId of 131 from C's namespace. E decapsulates.

3.6. Complex Tracks

To increase the reliability of the P2P transmission, this specification enables building a collection of Lanes between the same Ingress and Egress Nodes and combining them within the same TrackID, as shown in Figure 7. Lanes may cross at the edges of loose hops or remain parallel.

The Segments that join the loose hops of a Lane are installed with the same TrackID as the Lane. But each individual Lane and Segment has its own P-RouteID which allows it to be managed separately. 2 Lanes of the same Track may cross at a common node that participates to a Segment of Each Lane. In that case the common node has more than one next hop in its RIB associated to the Track, but no specific signal in the packet to indicate which Segment is being followed. A next hop that can reach the loose hop is selected.

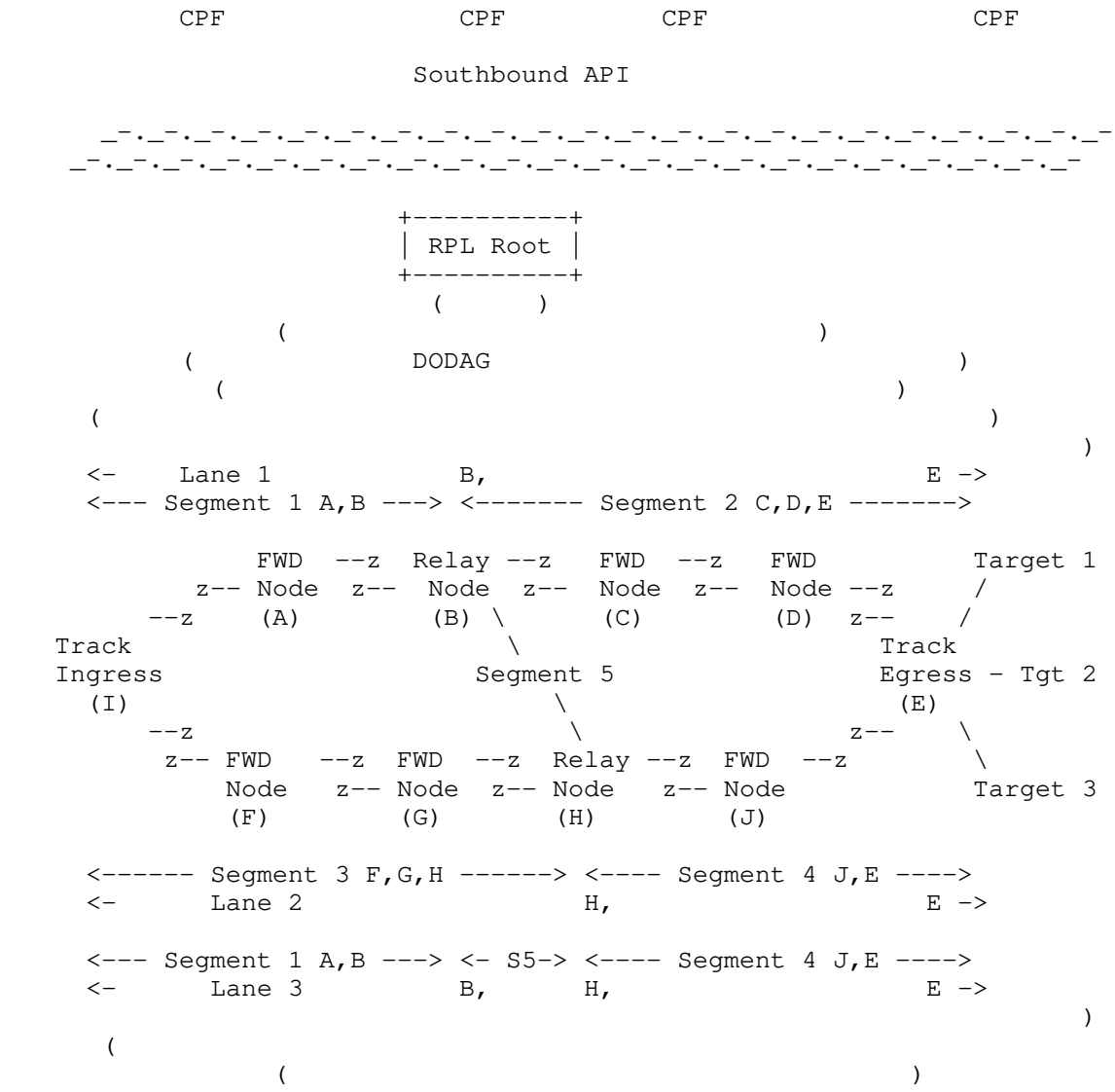


Figure 7: Segments and Tracks

Note that while this specification enables building both Segments inside a Lane (aka forward), such as Segment 2 above which is within Lane 1, and Inter-Lane Segments (aka North-South), such as Segment 5 above which joins Lane 1 and Lane 2, it does not signal to the Ingress which Inter-Lane Segments are available, so the use of North-South Segments and associated PAREO functions is curently limited. The only possibility available at this time is to define overlapping

Lanes as illustrated in Figure 7, with Lane 3 that is congruent with Lane 1 until node B and congruent with Lane 2 from node H on, abstracting Segment 5 as an forward Segment.

3.7. Scope and Expectations

3.7.1. External Dependencies

This specification expects that the main DODAG is operated in RPL Non-Storing Mode to sustain the exchanges with the Root. Based on its comprehensive knowledge of the parent-child relationship, the Root can form an abstracted view of the whole DODAG topology. This document adds the capability for nodes to advertise additional sibling information to complement the topological awareness of the Root to be passed on to the PCE, and enable the PCE to build more / better paths that traverse those siblings.

P-Routes require resources such as routing table space in the routers and bandwidth on the links; the amount of state that is installed in each node must be computed to fit within the node's memory, and the amount of rerouted traffic must fit within the capabilities of the transmission links. The methods used to learn the node capabilities and the resources that are available in the devices and in the network are out of scope for this document. The method to capture and report the LLN link capacity and reliability statistics are also out of scope. They may be fetched from the nodes through network management functions or other forms of telemetry such as OAM.

3.7.2. Positioning vs. Related IETF Standards

3.7.2.1. Extending 6TiSCH

The "6TiSCH Architecture" [RFC9030] leverages a centralized model that is similar to that of "Deterministic Networking Architecture" [RFC8655], whereby the device resources and capabilities are exposed to an external controller which installs routing states into the network based on its own objective functions that reside in that external entity.

3.7.2.2. Mapping to DetNet

DetNet Forwarding Nodes only understand the simple 1-to-1 forwarding sublayer transport operation along a Segment whereas the more sophisticated Relay nodes can also provide service sublayer functions such as Replication and Elimination.

One possible mapping between DetNet and this specification is to signal the Relay Nodes as the hops of a Lane and the forwarding Nodes as the hops in a Segment that join the Relay nodes as illustrated in Figure 7.

3.7.2.3. Leveraging PCE

With DetNet and 6TiSCH, the component of the controller that is responsible of computing routes is a PCE. The PCE computes its routes based on its own objective functions such as described in [RFC4655], and typically controls the routes using the PCE Protocol (PCEP) by [RFC5440]. While this specification expects a PCE and while PCEP might effectively be used between the Root and the PCE, the control protocol between the PCE and the Root is out of scope.

This specification also expects a single PCE with a full view of the network. Distributing the PCE function for a large network is out of scope. This specification uses the RPL Root as a proxy to the PCE. The PCE may be collocated with the Root, or may reside in an external Controller. In that case, the protocol between the Root and the PCE is out of scope and abstracted by / mapped to RPL inside the DODAG; one possibility is for the Root to transmit the RPL DAOs with the SIOs that detail the parent/child and sibling information.

The algorithm to compute the paths, the protocol used by the PCE and the metrics and link statistics involved in the computation are also out of scope. The effectiveness of the route computation by the PCE depends on the quality of the metrics that are reported from the RPL network. Which metrics are used and how they are reported is out of scope, but the expectation is that they are mostly of a long-term, statistical nature, and provide visibility on link throughput, latency, stability and availability over relatively long periods.

3.7.2.4. Providing for RAW

The RAW Architecture [RAW-ARCHI] extends the definition of Track, as being composed of forward directional Segments and North-South bidirectional Segments, to enable additional path diversity, using Packet ARQ, Replication, Elimination, and Overhearing (PAREO) functions over the available paths, to provide a dynamic balance between the reliability and availability requirements of the flows and the need to conserve energy and spectrum. This specification prepares for RAW by setting up the Tracks, but only forms DODAGs, which are composed of aggregated end-to-end loose source routed Lanes, joined by strict routed Segments, all oriented forward.

The RAW Architecture defines a dataplane extension of the PCE called the Point of Local Repair (PLR), that adapts the use of the path redundancy within a Track to defeat the diverse causes of packet loss. The PLR controls the forwarding operation of the packets within a Track. This specification can use but does not impose a PLR and does not provide the policies that would select which packets are routed through which path within a Track, in other words, how the PLR may use the path redundancy within the Track. By default, the use of the available redundancy is limited to simple load balancing, and all the Segments are forward unidirectional only.

A Track may be set up to reduce the load around the Root, or to enable urgent traffic to flow more directly. This specification does not provide the policies that would decide which flows are routed through which Track. In a Non-Storing Mode RPL Instance, the main DODAG provides a default route via the Root, and the Tracks provide more specific routes to the Track Targets.

4. Extending existing RFCs

This section explains which changes are extensions to existing specifications, and which changes are amendments to existing specifications. It is expected that extensions to existing specifications do not cause existing code on legacy 6LRs to malfunction, as the extensions will simply be ignored. New code is required for an extension. Those 6LRs will be unable to participate in the new mechanisms, but may also cause projected DAOs to be impossible to install. Amendments to existing specifications are situations where there are semantic changes required to existing code, and which may require new unit tests to confirm that legacy operations will continue unaffected.

4.1. Extending RFC 6550

This specification Extends RPL [RPL] to enable the Root to install forward routes inside a main DODAG that is operated as Non-Storing Mode. The Root issues a Projected DAO (P-DAO) message (see Section 4.1.1) to the Track Ingress; the P-DAO message contains a new Via Information Option (VIO) that installs a strict or a loose sequence of hops to form a Track Segment or a lane, respectively.

The P-DAO Request (PDR) is a new message detailed in Section 5.1. As per [RPL] section 6, if a node receives this message and it does not understand this new Code, it then discards the message. When the Root initiates communication to a node that it has not communicated with before and which it has not ascertained to implement this specification (by means such as capabilities), then the Root SHOULD request a PDR-ACK.

A P-DAO Request (PDR) message enables a Track Ingress to request the Track from the Root. The resulting Track is also a DODAG for which the Track Ingress is the Root, the owner the address that serves as DODAGID and authoritative for the associated namespace from which the TrackID is selected. In the context of this specification, the installed route appears as a more specific route to the Track Targets, and the Track Ingress forwards the packets towards the Targets via the Track using normal longest match IP forwarding.

To ensure that the PDR and P-DAO messages can flow at most times, it is RECOMMENDED that the nodes involved in a Track maintain multiple parents in the main DODAG, advertise them all to the Root, and use them in turn to retry similar packets. It is also RECOMMENDED that the Root uses diverse source route paths to retry similar messages to the nodes in the Track.

4.1.1. Projected DAO

Section 6 of [RPL] introduces the RPL Control Message Options (CMO), including the RPL Target Option (RTO) and Transit Information Option (TIO), which can be placed in RPL messages such as the destination Advertisement Object (DAO). A DAO message signals routing information to one or more Targets indicated in RTOs, providing one hop information at a time in the TIO.

This document Amends the specification of the DAO to create the P-DAO message. This Amended DAO is signaled with a new "Projected DAO" (P) flag, see Figure 8.

A Projected DAO (P-DAO) is a special DAO message generated by the Root to install a P-Route formed of multiple hops in its DODAG. This provides a RPL-based method to install the Tracks as expected by the 6TiSCH Architecture [RFC9030] as a collection of multiple P-Routes.

The Root MUST source the P-DAO message with its address that serves as DODAGID for the main DODAG. The receiver MUST NOT accept a P-DAO message that is not sent by the Root of its DODAG and MUST ignore such messages silently.

The 'P' flag is encoded in bit position 2 (to be confirmed by IANA) of the Flags field in the DAO Base Object. The Root MUST set it to 1 in a Projected DAO message. Otherwise it MUST be set to 0. It is set to 0 in Legacy implementations as specified respectively in Sections 20.11 and 6.4 of [RPL].

The P-DAO is a part of control plane signaling and should not be stuck behind high traffic levels. The expectation is that the P-DAO message is sent at high QoS level, above that of data traffic, typically with the Network Control precedence.

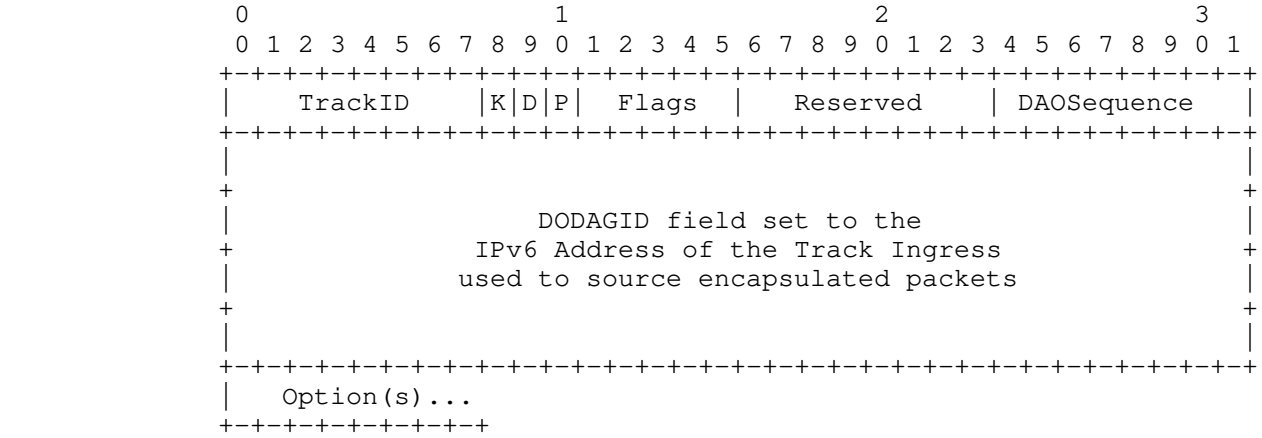


Figure 8: Projected DAO Base Object

New fields:

TrackID: The local or global RPLInstanceID of the DODAG that serves as Track (more in Section 6.3).

P: 1-bit flag (position to be confirmed by IANA).

The 'P' flag is set to 1 by the Root to signal a Projected DAO, and it is set to 0 otherwise.

The D flag is set to one to signal that the DODAGID field is present. It may be set to zero if and only if the destination address of the P-DAO-ACK message is set to the IPv6 address that serves as DODAGID and it MUST be set to one otherwise, meaning that the DODAGID field MUST then be present.

In RPL Non-Storing Mode, the TIO and RTO are combined in a DAO message to inform the DODAG Root of all the edges in the DODAG, which are formed by the directed parent-child relationships. The DAO message signals to the Root that a given parent can be used to reach a given child. The P-DAO message generalizes the DAO to signal to the Track Ingress that a Track for which it is Root can be used to reach children and siblings of the Track Egress. In both cases, options may be factorized and multiple RTOs may be present to signal a collection of children that can be reached through the parent or the Track, respectively.

4.1.2. Projected DAO-ACK

This document also Amends the DAO-ACK message. The new P flag signals the projected form.

The format of the P-DAO-ACK message is thus as illustrated in Figure 9:

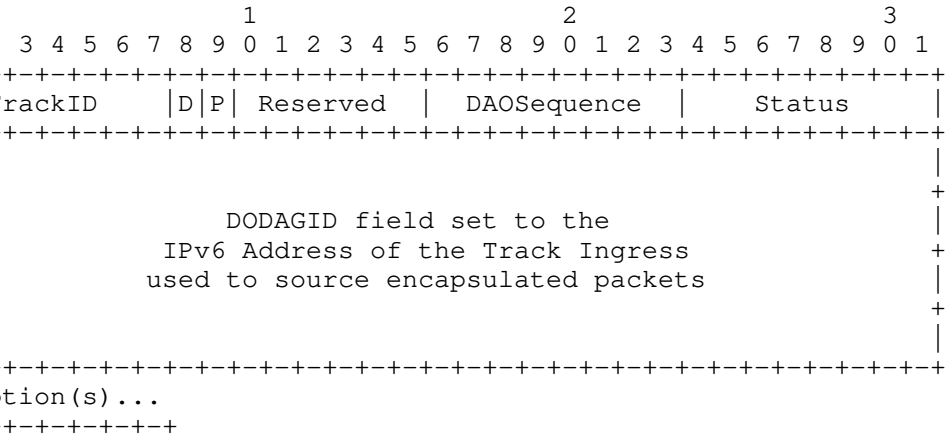


Figure 9: Projected DAO-ACK Base Object

New fields:

TrackID: The local or global RPLInstanceID of the DODAG that serves as Track (more in Section 6.3).

P: 1-bit flag (position to be confirmed by IANA).

The 'P' flag is set to 1 by the Root to signal a Projected DAO, and it is set to 0 otherwise.

The D flag is set to one to signal that the DODAGID field is present. It may be set to zero if and only if the source address of the P-DAO-ACK message is set to the IPv6 address that serves as DODAGID and it MUST be set to one otherwise, meaning that the DODAGID field MUST then be present.

4.1.3. Via Information Option

This document Extends the CMO to create new objects called the Via Information Options (VIO). The VIOs are the multihop alternative to the TIO (more in Section 5.3). One VIO is the stateful Storing Mode VIO (SM-VIO); an SM-VIO installs a strict hop-by-hop P-Route called a Track Segment. The other is the Non-Storing Mode VIO (NSM-VIO); the NSM-VIO installs a loose source-routed P-Route called a lane at the Track Ingress, which uses that state to encapsulate a packet IPv6_in_IPv6 with a new Routing Header (RH) to the Track Egress (more in Section 6.7).

A P-DAO contains one or more RTOs to indicate the Target (destinations) that can be reached via the P-Route, followed by exactly one VIO that signals the sequence of nodes to be followed (more in Section 6). There are two modes of operation for the P-Routes, the Storing Mode and the Non-Storing Mode, see Section 6.4.2 and Section 6.4.3 respectively for more.

4.1.4. Sibling Information Option

This specification Extends the CMO to create the Sibling Information Option (SIO). The SIO is used by a RPL Aware Node (RAN) to advertise a selection of its candidate neighbors as siblings to the Root (more in Section 5.4). The SIO is placed in DAO messages that are sent directly to the main Root, including multicast DAO (see section 9.10 of [RPL]).

This draft AMENDS the multicast DAO operation as follows:

1. A multicast DAO message MUST be used only to advertise information about the node (using the Target Option), and direct Link Neighbors such as learned by Neighbor Discovery (using the Sibling Information Option).

2. The multicast DAO may be used to enable direct and indirect (via a common neighbor) P2P communication without needing the DODAG to relay the packets. The multicast DAO exposes the sender's addresses as Targets in RTOs and the sender's neighbors addresses as siblings in SIOs; this tells the sender's neighbors that the sender is willing to act as a relay between those of its neighbors that are too far apart.

4.1.5. P-DAO Request

The set of RPL Control Messages is Extended to include the P-DAO Request (PDR) and P-DAO Request Acknowledgement (PDR-ACK). These two new RPL Control Messages enable an RPL-Aware Node to request the establishment of a Track between itself as the Track Ingress Node and a Track Egress. The node makes its request by sending a new P-DAO Request (PDR) Message to the Root. The Root confirms with a new PDR-ACK message back to the requester RAN, see Section 5.1 for more.

4.1.6. Amending the RPI

Sending a Packet within a RPL Local Instance requires the presence of the abstract RPL Packet Information (RPI) described in section 11.2. of [RPL] in the outer IPv6 Header chain (see [RFC9008]). The RPI carries a local RPLInstanceID which, in association with either the source or the destination address in the IPv6 Header, indicates the RPL Instance that the packet follows.

This specification Amends [RPL] to create a new flag that signals that a packet is forwarded along a P-Route.

Projected-Route 'P': 1-bit flag. It is set to 1 in the RPI that is added in the encapsulation when a packet is sent over a Track. It is set to 0 when a packet is forwarded along the main DODAG (as a Track), including when the packet follows a Segment that joins loose hops of the main DODAG. The flag is not mutable en-route.

The encoding of the 'P' flag in native format is shown in Section 4.2 while the compressed format is indicated in Section 4.3.

4.1.7. Additional Flag in the RPL DODAG Configuration Option

The DODAG Configuration Option is defined in Section 6.7.6 of [RPL]. Its purpose is extended to distribute configuration information affecting the construction and maintenance of the DODAG, as well as operational parameters for RPL on the DODAG, through the DODAG. This Option was originally designed with 4 bit positions reserved for future use as Flags.

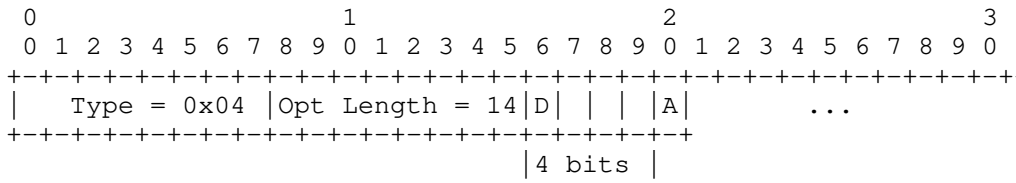


Figure 10: DODAG Configuration Option (Partial View)

This specification Amends the specification to define a new flag "Projected Routes Support" (D). The 'D' flag is encoded in bit position 0 of the reserved Flags in the DODAG Configuration Option (this is the most significant bit)(to be confirmed by IANA but there's little choice). It is set to 0 in legacy implementations as specified respectively in Sections 20.14 and 6.7.6 of [RPL].

The 'D' flag is set to 1 to indicate that this specification is enabled in the network and that the Root will install the requested Tracks when feasible upon a PDR message.

Section 4.1.2. of [RFC9008] Amends [RPL] to indicate that the definition of the Flags applies to Mode of Operation values from zero (0) to six (6) only. For a MOP value of 7, the implementation MUST consider that the Root accepts PDR messages and will install Projected Routes.

The RPL DODAG Configuration option is typically placed in a DODAG Information Object (DIO) message. The DIO message propagates down the DODAG to form and then maintain its structure. The DODAG Configuration option is copied unmodified from parents to children.

[RPL] states that:

> Nodes other than the DODAG root MUST NOT modify this information when propagating the DODAG Configuration option.

Therefore, a legacy parent propagates the 'D' flag as set by the root, and when the 'D' flag is set to 1, it is transparently flooded to all the nodes in the DODAG.

4.2. Extending RFC 6553

"The RPL Option for Carrying RPL Information in Data-Plane Datagrams" [RFC6553] describes the RPL Option for use among RPL routers to include the abstract RPL Packet Information (RPI) described in section 11.2. of [RPL] in data packets.

The RPL Option is commonly referred to as the RPI though the RPI is really the abstract information that is transported in the RPL Option. [RFC9008] updated the Option Type from 0x63 to 0x23.

This specification Amends the RPL Option to encode the 'P' flag as follows:

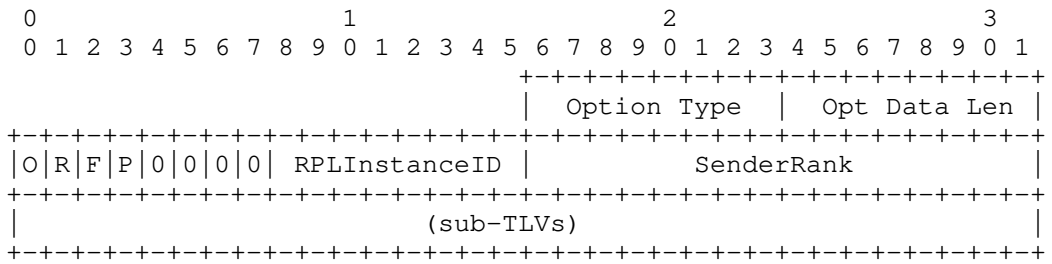


Figure 11: Amended RPL Option Format

Option Type: 0x23 or 0x63, see [RFC9008]

Opt Data Len: See [RFC6553]

'O', 'R' and 'F' flags: See [RFC6553]. Those flags MUST be set to 0 by the sender and ignored by the receiver if the 'P' flag is set.

Projected-Route 'P': 1-bit flag as defined in Section 4.1.6.

RPLInstanceID: See [RFC6553]. Indicates the TrackId if the 'P' flag is set, as discussed in Section 4.1.1.

SenderRank: See [RFC6553]. This field MUST be set to 0 by the sender and ignored by the receiver if the 'P' flag is set.

4.3. Extending RFC 8138

The 6LoWPAN Routing Header [RFC8138] specification introduces a new IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) [RFC6282] dispatch type for use in 6LoWPAN route-over topologies, which initially covers the needs of RPL data packet compression.

Section 4 of [RFC8138] presents the generic formats of the 6LoWPAN Routing Header (6LoRH) with two forms, one Elective that can be ignored and skipped when the router does not understand it, and one Critical which causes the packet to be dropped when the router cannot process it. The 'E' Flag in the 6LoRH indicates its form. In order to skip the Elective 6LoRHs, their format imposes a fixed expression of the size, whereas the size of a Critical 6LoRH may be signaled in variable forms to enable additional optimizations.

When the [RFC8138] compression is used, the Root of the main DODAG that sets up the Track also constructs the compressed routing header (SRH-6LoRH) on behalf of the Track Ingress, which saves the complexities of optimizing the SRH-6LoRH encoding in constrained code. The SRH-6LoRH is signaled in the NSM-VIO, in a fashion that it is ready to be placed as is in the packet encapsulation by the Track Ingress.

Section 6.3 of [RFC8138] presents the formats of the 6LoWPAN Routing Header of type 5 (RPI-6LoRH) that compresses the RPI for normal RPL operation. The format of the RPI-6LoRH is not suited for P-Routes since the O,R,F flags are not used and the Rank is unknown and ignored.

This specification extends [RFC8138] to introduce a new 6LoRH, the P-RPI-6LoRH that can be used in either Elective or Critical 6LoRH form, see Table 22 and Table 23 respectively. The new 6LoRH MUST be used as a Critical 6LoRH, unless an SRH-6LoRH is present and controls the routing decision, in which case it MAY be used in Elective form.

The P-RPI-6LoRH is designed to compress the RPI along RPL P-Routes. Its format is as follows:

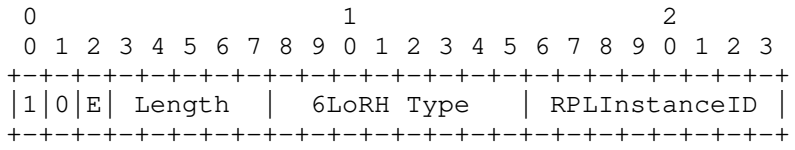


Figure 12: P-RPI-6LoRH Format

Type: IANA is requested to define the same value of the type for both Elective and Critical forms. A type of 8 is suggested.

Elective 'E': See [RFC8138]. The 'E' flag is set to 1 to indicate an Elective 6LoRH, meaning that it can be ignored when forwarding.

RPLInstanceID : In the context of this specification, the RPLInstanceID field signals the TrackID, see Section 3.4 and Section 6.3 .

Section 6.8 details how a Track Ingress leverages the P-RPI-6LoRH Header as part of the encapsulation of a packet to place it into a Track.

5. New RPL Control Messages and Options

5.1. New P-DAO Request Control Message

The P-DAO Request (PDR) message is sent by a Node in the main DODAG to the Root. It is a request to establish or refresh a Track where this node is Track Ingress, and signals whether an acknowledgment called PDR-ACK is requested or not. A positive PDR-ACK indicates that the Track was built and that the Root commits to maintaining the Track for the negotiated lifetime.

The main Root MAY indicate to the Track Ingress that the Track was terminated before its time and to do so, it MUST use an asynchronous PDR-ACK with a negative status. A status of "Transient Failure" (see Section 11.10) is an indication that the PDR may be retried after a reasonable time that depends on the deployment. Other negative status values indicate a permanent error; the attempt must be abandoned until a corrective action is taken at the application layer or through network management.

The source IPv6 address of the PDR signals the Track Ingress to-be of the requested Track, and the TrackID is indicated in the message itself. At least one RPL Target Option MUST be present in the message. If more than one RPL Target Option is present, the Root will provide a Track that reaches the first listed Target and a subset of the other Targets; the details of the subset selection are out of scope. The RTO signals the Track Egress (more in Section 6.2).

The RPL Control Code for the PDR is 0x09, to be confirmed by IANA. The format of PDR Base Object is as follows:

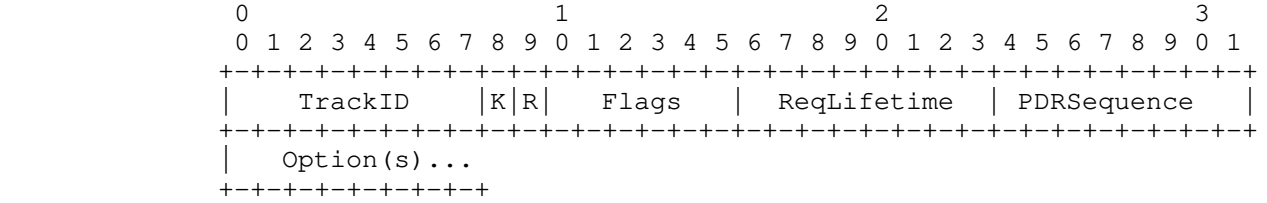


Figure 13: New P-DAO Request Format

TrackID: 8-bit field. In the context of this specification, the TrackID field signals the RPLInstanceID of the DODAG formed by the Track, see Section 3.4 and Section 6.3. To allocate a new Track, the Ingress Node must provide a value that is not in use at this time.

K: The 'K' flag is set to indicate that the recipient is expected to send a PDR-ACK back.

R: The 'R' flag is set to request a Complex Track for redundancy.

Flags: Reserved. The Flags field MUST be initialized to zero by the sender and MUST be ignored by the receiver.

ReqLifetime: 8-bit unsigned integer. The requested lifetime for the Track expressed in Lifetime Units (obtained from the DODAG Configuration option). The value of 255 (0xFF) represents infinity (never time out).

A PDR with a fresher PDRSequence refreshes the lifetime, and a PDRLifetime of 0 indicates that the Track should be destroyed, e.g., when the application that requested the Track terminates.

PDRSequence: 8-bit wrapping sequence number, obeying the operation in section 7.2 of [RPL]. The PDRSequence is used to correlate a PDR-ACK message with the PDR message that triggered it. It is incremented at each PDR message and echoed in the PDR-ACK by the Root.

5.2. New PDR-ACK Control Message

The new PDR-ACK is sent as a response to a PDR message with the 'K' flag set. The RPL Control Code for the PDR-ACK is 0x0A, to be confirmed by IANA. Its format is as follows:

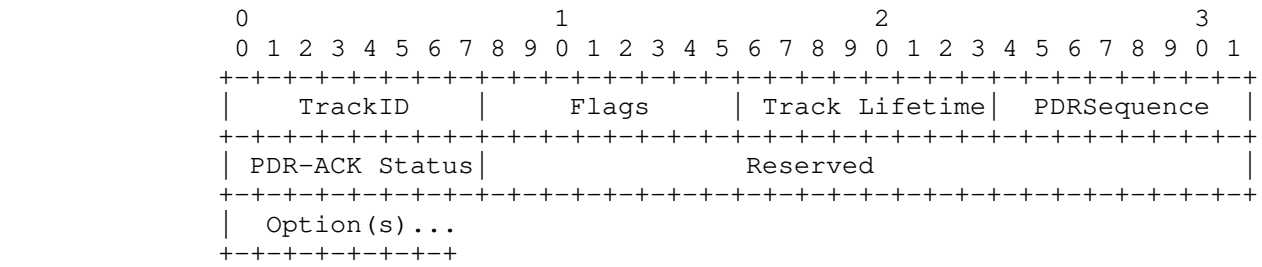


Figure 14: New PDR-ACK Control Message Format

TrackID: Set to the TrackID indicated in the TrackID field of the PDR messages that this replies to.

Flags: Reserved. The Flags field MUST be initialized to zero by the sender and MUST be ignored by the receiver.

Track Lifetime: Indicates the remaining Lifetime for the Track, expressed in Lifetime Units; The value of 255 (0xFF) represents infinity. The value of zero (0x00) indicates that the Track was destroyed or not created.

PDRSequence: 8-bit wrapping sequence number. It is incremented at each PDR message and echoed in the PDR-ACK.

PDR-ACK Status: 8-bit field indicating the completion. The PDR-ACK Status is substructured as indicated in Figure 15:

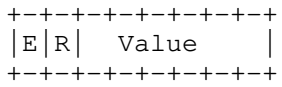


Figure 15: PDR-ACK status Format

E: 1-bit flag. Set to indicate a rejection. When not set, the value of 0 indicates Success/Unqualified Acceptance and other values indicate "not an outright rejection".
R: 1-bit flag. Reserved, MUST be set to 0 by the sender and ignored by the receiver.
Status Value: 6-bit unsigned integer. Values depending on the setting of the 'E' flag, see Table 28 and Table 29.

Reserved: The Reserved field MUST be initialized to zero by the sender and MUST be ignored by the receiver.

5.3. Via Information Options

A VIO signals the ordered list of IPv6 Via Addresses that constitutes the hops of either a Lane (using Non-Storing Mode) or a Segment (using Storing mode) of a Track. A Storing Mode P-DAO contains one Storing Mode VIO (SM-VIO) whereas a Non-Storing Mode P-DAO contains one Non-Storing Mode VIO (NSM-VIO).

The duration of the validity of a VIO is indicated in a Segment Lifetime field. A P-DAO message that contains a VIO with a Segment Lifetime of zero is referred as a No-Path P-DAO.

The VIO contains one or more SRH-6LoRH header(s), each formed of a SRH-6LoRH head and a collection of compressed Via Addresses, except in the case of a Non-Storing Mode No-Path P-DAO where the SRH-6LoRH header is not present.

In the case of a SM-VIO, or if [RFC8138] is not used in the data packets, then the Root MUST use only one SRH-6LoRH per Via Information Option, and the compression is the same for all the addresses, as shown in Figure 16, for simplicity.

In case of an NSM-VIO and if [RFC8138] is in use in the main DODAG, the Root SHOULD optimize the size of the NSM-VIO if using different SRH-6LoRH Types would make the VIO globally shorter; this means that more than one SRH-6LoRH may be present.

The format of the Via Information Option is as follows:

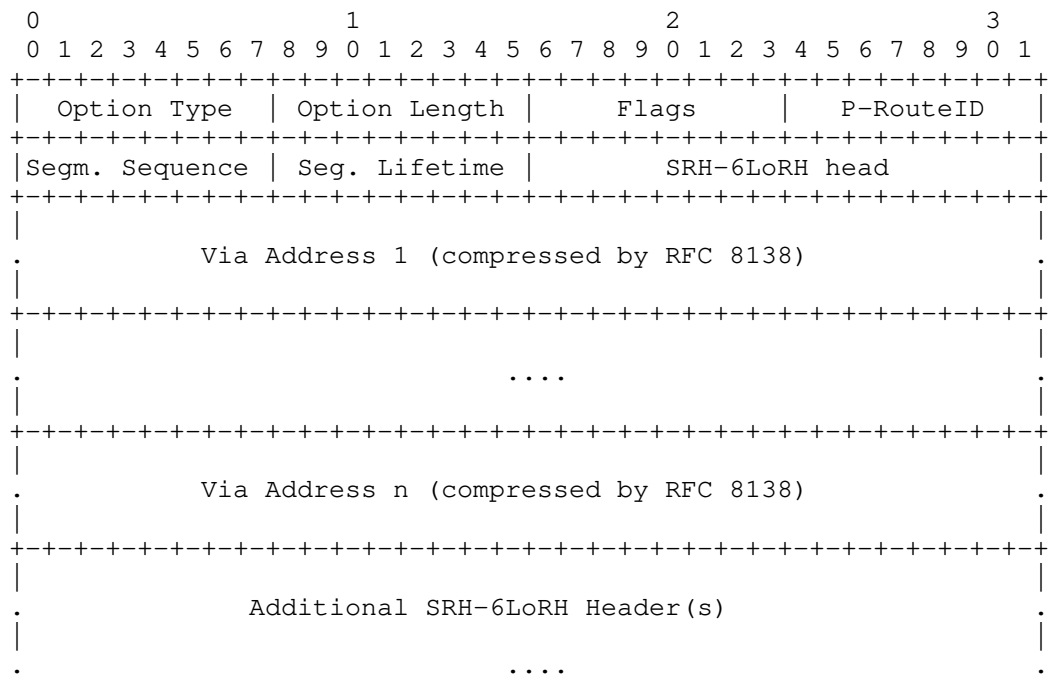


Figure 16: VIO format

Option Type: 0x0E for SM-VIO, 0x0F for NSM-VIO (to be confirmed by IANA) (see Table 26).

Option Length: 8-bit unsigned integer, representing the length in octets of the option, not including the Option Type and Length fields (see section 6.7.1. of [RPL]); the Option Length is variable, depending on the number of Via Addresses and the compression applied.

Flags: 8-bit field. No flag is defined in this specification. The field MUST be set to 0 by the sender and ignored by the receiver.

P-RouteID: 8-bit field that identifies a component of a Track or the

main DODAG as indicated by the TrackID field. The value of 0 is used to signal a path, i.e., made of a single Segment/Lane. In an SM-VIO, the P-RouteID indicates an actual Segment. In an NSM-VIO, it indicates a Lane, that is a path that is added to the overall topology of the Track.

Segment Sequence: 8-bit unsigned integer. The Segment Sequence obeys the operation in section 7.2 of [RPL] and the lollipop starts at 255.

When the Root of the DODAG needs to refresh or update a Segment in a Track, it increments the Segment Sequence individually for that Segment.

The Segment information indicated in the VIO deprecates any state for the Segment indicated by the P-RouteID within the indicated Track and sets up the new information.

A VIO with a Segment Sequence that is not as fresh as the current one is ignored.

A VIO for a given DODAGID with the same (TrackID, P-RouteID, Segment Sequence) indicates a retry; it MUST NOT change the Segment and MUST be propagated or answered as the first copy.

Segment Lifetime: 8-bit unsigned integer. The length of time in Lifetime Units (obtained from the Configuration option) that the Segment is usable.

The period starts when a new Segment Sequence is seen. The value of 255 (0xFF) represents infinity. The value of zero (0x00) indicates a loss of reachability.

SRH-6LoRH head: The first 2 bytes of the (first) SRH-6LoRH as shown in Figure 6 of [RFC8138]. As an example, a 6LoRH Type of 4 means that the VIA Addresses are provided in full with no compression.

Via Address: An IPv6 ULA or GUA of a node along the Segment. The VIO contains one or more IPv6 Via Addresses listed in the datapath order from Ingress to Egress. The list is expressed in a compressed form as signaled by the preceding SRH-6LoRH header.

In a Storing Mode P-DAO that updates or removes a section of an already existing Segment, the list in the SM-VIO may represent only the section of the Segment that is being updated; at the extreme, the SM-VIO updates only one node, in which case it contains only one IPv6 address. In all other cases, the list in the VIO MUST be complete.

In the case of an SM-VIO, the list indicates a sequential (strict) path through direct neighbors, the complete list starts at Ingress and ends at Egress, and the nodes listed in the VIO, including the Egress, MAY be considered as implicit Targets.

In the case of an NSM-VIO, the complete list can be loose and excludes the Ingress node, starting at the first loose hop and ending at a Track Egress; the Track Egress MUST be considered as an implicit Target, so it MUST NOT be signaled in a RPL Target Option.

5.4. Sibling Information Option

The Sibling Information Option (SIO) provides information about siblings that could be used by the Root to form P-Routes. One or more SIO(s) may be placed in the DAO messages that are sent to the Root in Non-Storing Mode.

To advertise a neighbor node, the router MUST have an active Address Registration from that sibling using [RFC8505], for an address (ULA or GUA) that serves as identifier for the node. If this router also registers an address to that sibling, and the link has similar properties in both directions, only the router with the lowest Interface ID in its registered address needs to report the SIO, with the B flag set, and the Root will assume symmetry.

The SIO carries a flag (B) that is set when similar performance can be expected in both directions, so the routing can consider that the information provided for one direction is valid for both. If the SIO is effectively received from both sides then the B flag MUST be ignored. The policy that describes the performance criteria, and how they are asserted is out of scope. In the absence of an external protocol to assert the link quality, the flag SHOULD NOT be set.

The format of the SIO is as follows:

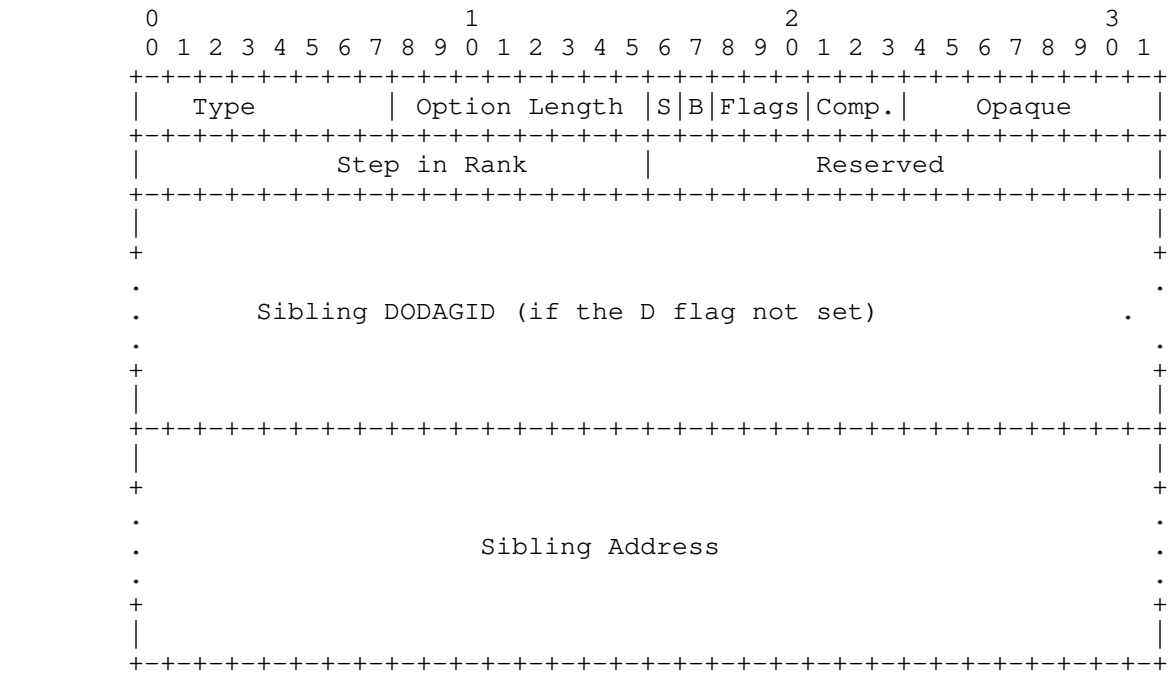


Figure 17: Sibling Information Option Format

Option Type: 0x10 for SIO (to be confirmed by IANA) (see Table 26).

Option Length: 8-bit unsigned integer, representing the length in octets of the option, not including the Option Type and Length fields (see section 6.7.1. of [RPL]).

Reserved for Flags: MUST be set to zero by the sender and MUST be ignored by the receiver.

B: 1-bit flag that is set to indicate that the connectivity to the sibling is bidirectional and roughly symmetrical. In that case, only one of the siblings may report the SIO for the hop. If 'B' is not set then the SIO only indicates connectivity from the sibling to this node, and does not provide information on the hop from this node to the sibling.

S: 1-bit flag that is set to indicate that sibling belongs to the same DODAG. When not set, the Sibling DODAGID is indicated.

Flags: Reserved. The Flags field MUST be initialized to zero by the sender and MUST be ignored by the receiver.

Opaque: MAY be used to carry information that the node and the Root understand, e.g., a particular representation of the Link properties such as a proprietary Link Quality Information for packets received from the sibling. In some scenarios such as the case of an Industrial Alliances that uses RPL for a particular use / environment, this field MAY be redefined to fit the needs of that case.

Compression Type: 3-bit unsigned integer. This is the SRH-6LoRH Type as defined in figure 7 in section 5.1 of [RFC8138] that corresponds to the compression used for the Sibling Address and its DODAGID if present. The Compression reference is the Root of the main DODAG.

Step in Rank: 16-bit unsigned integer. This is the Step in Rank [RPL] as computed by the Objective Function between this node and the sibling, that reflects the abstract Rank increment that would be computed by the OF if the sibling was the preferred parent.

Reserved: The Reserved field MUST be initialized to zero by the sender and MUST be ignored by the receiver

Sibling DODAGID: 2 to 16 bytes, the DODAGID of the sibling in a [RFC8138] compressed form as indicated by the Compression Type field. This field is present if and only if the D flag is not set.

Sibling Address: 2 to 16 bytes, an IPv6 Address of the sibling, with a scope that MUST be make it reachable from the Root, e.g., it cannot be a Link Local Address. The IPv6 address is encoded in the [RFC8138] compressed form indicated by the Compression Type field.

An SIO MAY be immediately followed by a DAG Metric Container. In that case the DAG Metric Container provides additional metrics for the hop from the Sibling to this node.

6. Root Initiated Routing State

6.1. RPL Network Setup

To avoid the need of Path MTU Discovery, 6LoWPAN links are normally defined with a MTU of 1280 (see section 4 of [6LoWPAN]). Injecting packets in a Track typically involves an IP-in-IP encapsulation and additional IPv6 Extension Headers. This may cause fragmentation if the resulting packets exceeds the MTU that is defined for the RPL domain.

Though fragmentation is possible in a 6LoWPAN LLN, e.g., using [6LoWPAN], [RFC8930], and/or [RFC8931], it is RECOMMENDED to allow an MTU that is larger than 1280 in the main DODAG and which allows for the additional headers while exposing only 1280 to the 6LoWPAN Nodes.

6.2. Requesting a Track

This specification introduces the PDR message, used by an LLN node to request the formation of a new Track for which this node is the Ingress. Note that the namespace for the TrackID is owned by the Ingress node, and in the absence of a PDR, there must be some procedure for the Root to assign TrackIDs in that namespace while avoiding collisions (more in Section 6.3).

The PDR signals the desired TrackID and the duration for which the Track should be established. Upon a PDR, the Root MAY install the Track as requested, in which case it answers with a PDR-ACK indicating the granted Track Lifetime. All the Segments MUST be of a same mode, either Storing or Non-Storing. All the Segments MUST be created with the same TrackID and the same DODAGID signaled in the P-DAO.

The Root designs the Track as it sees best, and updates / changes the Segments over time to serve the Track as needed. Note that there is no protocol element to notify to the requesting Track Ingress when changes happen deeper down the Track, so they are transparent to the Track Ingress. If the main Root cannot maintain an expected service level, then it needs to tear down the Track completely. The Segment Lifetime in the P-DAO messages does not need to be aligned to the Requested Lifetime in the PDR, or between P-DAO messages for different Segments. The Root may use shorter lifetimes for the Segments and renew them faster than the Track is, or longer lifetimes in which case it will need to tear down the Segments if the Track is not renewed.

When the Track Lifetime that was returned in the PDR-ACK is close to elaPLR - vs. the trip time from the node to the Root, the requesting node SHOULD resend a PDR using the TrackID in the PDR-ACK to extend the lifetime of the Track, else the Track will time out and the Root will tear down the whole structure.

If the Track fails and cannot be restored, the Root notifies the requesting node asynchronously with a PDR-ACK with a Track Lifetime of 0, indicating that the Track has failed, and a PDR-ACK Status indicating the reason of the fault.

6.3. Identifying a Track

RPL defines the concept of an Instance to signal an individual routing topology, and multiple topologies can coexist in the same network. The RPLInstanceID is tagged in the RPI of every packet to signal which topology the packet actually follows.

This draft leverages the RPL Instance model as follows:

* The main Root MAY use P-DAO messages to add better routes in the main Instance in conformance with the routing objectives in that Instance.

  To achieve this, the main Root MAY install a Segment along a path down the main DODAG, which is operated in Non-Storing Mode. This enables a loose source routing and reduces the size of the Routing Header, see Section 3.3.1. The main Root MAY also install a lane across the main DODAG to complement the routing topology.

  When adding a P-Route to the RPL main DODAG, the main Root MUST set the RPLInstanceID field of the P-DAO Base Object (see section 6.4.1. of [RPL]) to the RPLInstanceID of the main DODAG, and MUST NOT use the DODAGID field. A P-Route provides a longer match to the Target Address than the default route via the main Root, so it is preferred.

* The main Root MAY also use P-DAO messages to install a Track as an independent routing topology (say, Traffic Engineered) to achieve particular routing characteristics from an Ingress to Egress Endpoints. To achieve this, the main Root MUST set up a Local RPL Instance (see section 5 of [RPL]), and the Local RPLInstanceID serves as the TrackID. The TrackID MUST be unique for the IPv6 ULA or GUA of the Track Ingress that serves as DODAGID for the Track.

  This way, a Track is uniquely identified by the tuple (DODAGID, TrackID) where the TrackID is always represented with the D flag set to 0 (see also section 5.1. of [RPL]), indicating when used in an RPI that the source address of the IPv6 packet signals the DODAGID.

  The P-DAO Base Object MUST indicate the tuple (DODAGID, TrackID) that identifies the Track as shown in Figure 8, and the P-RouteID that identifies the P-Route MUST be signaled in the VIO as shown in Figure 16.

The Track Ingress is the Root of the DODAG ID formed by the local RPL Instance. It owns the namespace of its TrackIDs, so it can pick any unused value to request a new Track with a PDR. In a particular deployment where PDRs are not used, a portion of the namespace can be administratively delegated to the main Root, meaning that the main Root is authoritative for assigning the TrackIDs for the Tracks it creates.

With this specification, the main Root is aware of all the active Tracks, so it can also pick any unused value to form Tracks without a PDR. To avoid a collision of the main Root and the Track Ingress picking the same value at the same time, it is RECOMMENDED that the Track Ingress starts allocating the ID value of the Local RPLInstanceID (see section 5.1. of [RPL]) used as TrackIDs with the value 0 incrementing, while the Root starts with 63 decrementing.

6.4. Installing a Track

A path can be installed by a single P-Route that signals the sequence of consecutive nodes, either in Storing Mode as a single-Segment Track, or in Non-Storing Mode as a single-Lane Track. A single-Lane Track can be installed as a loose Non-Storing Mode P-Route, in which case the next loose entry must recursively be reached over a path.

A Complex Track can be installed as a collection of P-Routes with the same DODAGID and Track ID. The Ingress of a Non-Storing Mode P-Route is the owner and Root of the DODAGID. The Ingress of a Storing Mode P-Route must be either the owner of the DODAGID, or a hop of a Lane of the same Track. In the latter case, the Targets of the P-Route must include the next hop of the Lane if there is one, to ensure forwarding continuity. In the case of a Complex Track, each Segment is maintained independently and asynchronously by the Root, with its own lifetime that may be shorter, the same, or longer than that of the Track.

A route along a Track for which the TrackID is not the RPLInstanceID of the main DODAG MUST be installed with a higher precedence than the routes along the main DODAG, meaning that:

* Longest match MUST be the prime comparison for routing.

* In case of equal length match, the route along the Track MUST be preferred vs. the one along the main DODAG.

* There SHOULD NOT be 2 different Tracks leading to the same Target from same Ingress node, unless there’s a policy for selecting which packets use which Track; such a policy is out of scope.

* A packet that was routed along a Track MUST NOT be routed along the main DODAG again; if the destination is not reachable as a neighbor by the node where the packet exits the Track then the packet MUST be dropped.

6.4.1. Signaling a Projected Route

This draft adds a capability whereby the Root of a main DODAG installs a Track as a collection of P-Routes, using a Projected-DAO (P-DAO) message for each individual lane or Segment. The P-DAO signals a collection of Targets in the RPL Target Option(s) (RTO). Those Targets can be reached via a sequence of routers indicated in a VIO.

Like a classical DAO message, a P-DAO causes a change of state only if it is "new" per section 9.2.2. "Generation of DAO Messages" of the RPL specification [RPL]; this is determined using the Segment Sequence information from the VIO as opposed to the Path Sequence from a TIO. Also, a Segment Lifetime of 0 in a VIO indicates that the P-Route associated to the Segment is to be removed. There are two Modes of operation for the P-Routes, the Storing and the Non-Storing Modes.

A P-DAO message MUST be sent from the address of the Root that serves as DODAGID for the main DODAG. It MUST contain either exactly one sequence of one or more RTOs followed one VIO, or any number of sequences of one or more RTOs followed by one or more TIOs. The former is the normal expression for this specification, where as the latter corresponds to the variation for lesser constrained environments described in Section 7.2.

A P-DAO that creates or updates a lane MUST be sent to a GUA or a ULA of the Ingress of the Lane; it must contain the full list of hops in the Lane unless the Lane is being removed. A P-DAO that creates a new Track Segment MUST be sent to a GUA or a ULA of the Segment Egress and MUST signal the full list of hops in Segment; a P-DAO that updates (including deletes) a section of a Segment MUST be sent to the first node after the modified Segment and signal the full list of hops in the section starting at the node that immediately precedes the modified section.

In Non-Storing Mode, as discussed in Section 6.4.3, the Root sends the P-DAO to the Track Ingress where the source-routing state is applied, whereas in Storing Mode, the P-DAO is sent to the last node on the installed path and forwarded in the reverse direction, installing a Storing Mode state at each hop, as discussed in Section 6.4.2. In both cases the Track Ingress is the owner of the Track, and it generates the P-DAO-ACK when the installation is successful.

If the 'K' Flag is present in the P-DAO, the P-DAO must be acknowledged using a DAO-ACK that is sent back to the address of the Root from which the P-DAO was received. In most cases, the first node of the Lane, Segment, or updated section of the Segment is the node that sends the acknowledgment. The exception to the rule is when an intermediate node in a Segment fails to forward a Storing Mode P-DAO to the previous node in the SM-VIO.

In a No-Path Non-Storing Mode P-DAO, the SRH-6LoRH MUST NOT be present in the NSM-VIO; the state in the Ingress is erased regardless. In all other cases, a VIO MUST contain at least one Via Address, and a Via Address MUST NOT be present more than once, which would create a loop.

A node that processes a VIO MAY verify whether any of these conditions happen, and when one does, it MUST ignore the P-DAO and reject it with a RPL Rejection Status of "Error in VIO" in the DAO-ACK, see Section 11.16.

Other errors than those discussed explicitly that prevent the installation of the route are acknowledged with a RPL Rejection Status of "Unqualified Rejection" in the DAO-ACK.

6.4.2. Installing a Track Segment with a Storing Mode P-Route

As illustrated in Figure 18, a Storing Mode P-DAO installs a route along the Segment signaled by the SM-VIO towards the Targets indicated in the Target Options. The Segment is to be included in a DODAG indicated by the P-DAO Base Object, that may be the one formed by the main DODAG, or a Track associated with a local RPL Instance.

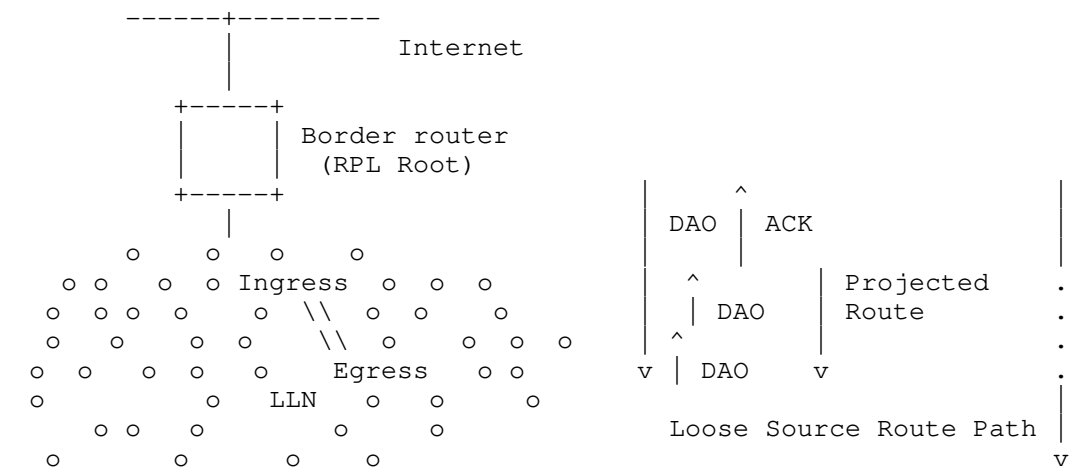


Figure 18: Projecting a route

In order to install the relevant routing state along the Segment , the Root sends a unicast P-DAO message to the Track Egress router of the routing Segment that is being installed. The P-DAO message contains a SM-VIO with the strict sequence of Via Addresses. The SM-VIO follows one or more RTOs indicating the Targets to which the Track leads. The SM-VIO contains a Segment Lifetime for which the state is to be maintained.

The Root sends the P-DAO directly to the Egress node of the Segment. In that P-DAO, the destination IP address matches the last Via Address in the SM-VIO. This is how the Egress recognizes its role. In a similar fashion, the Segment Ingress node recognizes its role because it matches the first Via Address in the SM-VIO.

The Egress node of the Segment is the only node in the path that does not install a route in response to the P-DAO; it is expected to be already able to route to the Target(s) based on its existing tables. If one of the Targets is not known, the node MUST answer to the Root with a DAO-ACK listing the unreachable Target(s) in an RTO and a rejection status of "Unreachable Target".

If the Egress node can reach all the Targets, then it forwards the P-DAO with unchanged content to its predecessor in the Segment as indicated in the list of Via Information options, and recursively the message is propagated unchanged along the sequence of routers indicated in the P-DAO, but in the reverse order, from Egress to Ingress.

The address of the predecessor to be used as destination of the propagated DAO message is found in the Via Address list, at the position preceeding the one that contains the address of the propagating node, which is used as source of the message.

Upon receiving a propagated DAO, all except the Egress router MUST install a route towards the DAO Target(s) via their successor in the SM-VIO. A router that cannot store the routes to all the Targets in a P-DAO MUST reject the P-DAO by sending a DAO-ACK to the Root with a Rejection Status of "Out of Resources" as opposed to forwarding the DAO to its predecessor in the list. The router MAY install additional routes towards the Via Addresses that appear in the SM-VIO after its own address, if any, but in case of a conflict or a lack of resource, the route(s) to the Target(s) are the ones that must be installed in priority.

If a router cannot reach its predecessor in the SM-VIO, the router MUST send the DAO-ACK to the Root with a Rejection Status of "Predecessor Unreachable".

The process continues until the P-DAO is propagated to the Ingress router of the Segment, which answers with a DAO-ACK to the Root. The Root always expects a DAO-ACK, either from the Track Ingress with a positive status or from any node along the Segment with a negative status. If the DAO-ACK is not received, the Root may retry the DAO with the same TID, or tear down the route.

6.4.3. Installing a lane with a Non-Storing Mode P-Route

As illustrated in Figure 19, a Non-Storing Mode P-DAO installs a source-routed path within the Track indicated by the P-DAO Base Object, towards the Targets indicated in the Target Options. The source-routed path requires a Source-Routing header which implies an IP-in-IP encapsulation to add the SRH to an existing packet. It is sent to the Track Ingress which creates a tunnel associated with the Track, and connected routes over the tunnel to the Targets in the RTO. The tunnel encapsulation MUST incorporate a routing header via the list addresses listed in the VIO in the same order. The content of the NSM-VIO starting at the first SRH-6LoRH header MUST be used verbatim by the Track Ingress when it encapsulates a packet to forward it over the Track.

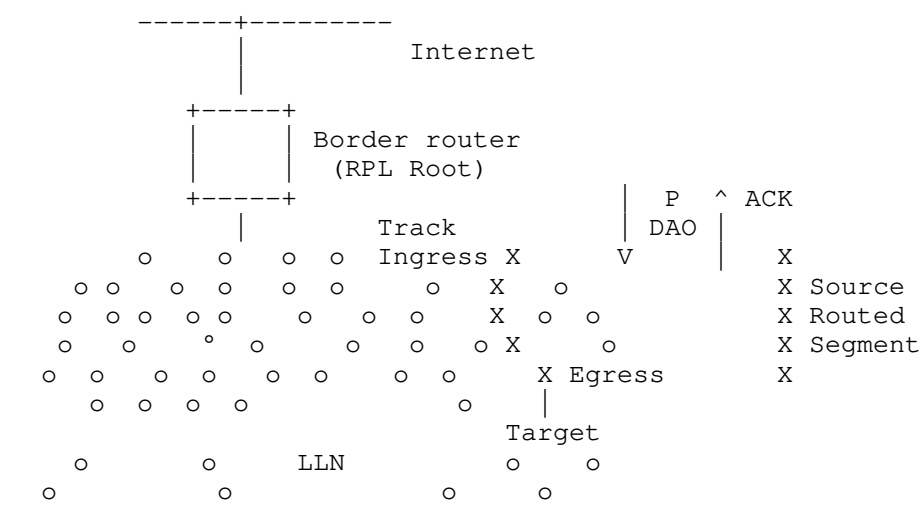


Figure 19: Projecting a Non-Storing Route

The next entry in the source-routed path must be either a neighbor of the previous entry, or reachable as a Target via another P-Route, either Storing or Non-Storing, which implies that the nested P-Route has to be installed before the loose sequence is, and that P-Routes must be installed from the last to the first along the datapath. For instance, a Segment of a Track must be installed before the Lane(s) of the same Track that use it, and stitched Segments must be installed in order from the last that reaches to the Targets to the first.

If the next entry in the loose sequence is reachable over a Storing Mode P-Route, it MUST be the Target of a Segment and the Ingress of a next Segment, both already setup; the Segments are associated with the same Track, which avoids the need of an additional encapsulation. For instance, in Section 3.5.1.3, Segments A==>B-to-C and C==>D==>E-to-F must be installed with Storing Mode P-DAO messages 1 and 2 before the Track A-->C-->E-to-F that joins them can be installed with Non-Storing Mode P-DAO 3.

Conversely, if it is reachable over a Non-Storing Mode P-Route, the next loose source-routed hop of the inner Track is a Target of a previously installed Track and the Ingress of a next Track, which requires a de- and a re-encapsulation when switching the outer Tracks that join the loose hops. This is examplified in Section 3.5.2.3 where Non-Storing Mode P-DAO 1 and 2 install strict Tracks that Non-Storing Mode P-DAO 3 joins as a super Track. In such a case, packets are subject to double IP-in-IP encapsulation.

6.5. Tearing Down a P-Route

A P-DAO with a lifetime of 0 is interpreted as a No-Path DAO and results in cleaning up existing state as opposed to refreshing an existing one or installing a new one. To tear down a Track, the Root must tear down all the Track Segments and Lanes that compose it one by one.

Since the state about a Lane of a Track is located only on the Ingress Node, the Root cleans up the Lane by sending an NSM-VIO to the Ingress indicating the TrackID and the P-RouteID of the Lane being removed, a Segment Lifetime of 0 and a newer Segment Sequence. The SRH-6LoRH with the Via Addresses in the NSM-VIO are not needed; it SHOULD NOT be placed in the message and MUST be ignored by the receiver. Upon that NSM-VIO, the Ingress node removes all state for that Track if any, and replies positively anyway.

The Root cleans up a section of a Segment by sending an SM-VIO to the last node of the Segment, with the TrackID and the P-RouteID of the Segment being updated, a Segment Lifetime of zero (0) and a newer Segment Sequence. The Via Addresses in the SM-VIO indicates the section of the Segment being modified, from the first to the last node that is impacted. This can be the whole Segment if it is totally removed, or a sequence of one or more nodes that have been bypassed by a Segment update.

The No-Path P-DAO is forwarded normally along the reverse list, even if the intermediate node does not find a Segment state to clean up. This results in cleaning up the existing Segment state if any, as opposed to refreshing an existing one or installing a new one.

6.6. Maintaining a Track

Repathing a Track Segment or Lane may cause jitter and packet misordering. For critical flows that require timely and/or in-order delivery, it might be necessary to deploy the PAREO functions [RAW-ARCHI] over a highly redundant Track. This specification allows to use more than one Lane for a Track, and 1+N packet redundancy.

This section provides the steps to ensure that no packet is lost due to the operation itself. This is ensured by installing the new section from its last node to the first, so when an intermediate node installs a route along the new section, all the downstream nodes in the section have already installed their own. The disabled section is removed when the packets in-flight are forwarded along the new section as well.

6.6.1. Maintaining a Track Segment

To modify a section of a Segment between a first node and a second, downstream node (which can be the Ingress and Egress, respectively), while retaining those nodes in the Segment, the Root sends an SM-VIO to the second node indicating the sequence of nodes in the new section of the Segment. The SM-VIO indicates the TrackID and the P-RouteID of the Segment being updated, and a newer Segment Sequence. The P-DAO is propagated from the second to the first node and on the way, it updates the state on the nodes that are common to the old and the new section of the Segment and creates a state in the new nodes.

When the state is updated in an intermediate node, that node might still receive packets that were in flight from the Ingress to self over the old section of the Segment. Since the remainder of the Segment is already updated, the packets are forwarded along the new version of the Segment from that node on.

After a reasonable time to enable the deprecated sections to drain their traffic, the Root tears down the remaining section(s) of the old Segments as described in Section 6.5.

6.6.2. Maintaining a lane

This specification allows the Root to add Lanes to a Track by sending a Non-Storing Mode P-DAO to the Ingress associated to the same TrackID, and a new Segment ID. If the Lane is loose, then the Segments that join the hops must be created first. It makes sense to add a new Lane before removing one that is becoming excessively lossy, and switch to the new Lane before removing the old. Dropping a Track before the new one is installed would reroute the traffic via the root; this may increase the latency beyond acceptable thresholds, and overload the network near the root. This may also cause loops in the case of stitched Tracks: the packets that cannot be injected in the second Track might be routed back and reinjected at the Ingress of the first.

It is also possible to update a lane by sending a Non-Storing Mode P-DAO to the Ingress with the same Segment ID, an incremented Segment Sequence, and the new complete list of hops in the NSM-VIO. Updating a live Lane means changing one or more of the intermediate loose hops, and involves laying out new Segments from and to the new loose hops before the NSM-VIO for the new Lane is issued.

Packets that are in flight over the old version of the lane still follow the old source route path over the old Segments. After a reasonable time to enable the deprecated Segments to drain their traffic, the Root tears down those Segments as described in Section 6.5.

6.7. Encapsulating and Forwarding Along a Track

When injecting a packet in a Track, the Ingress router must encapsulate the packet using IP-in-IP to add the Source Routing Header with the final destination set to the Track Egress.

All properties of a Track operations are inherited form the main Instance that is used to install the Track. For instance, the use of compression per [RFC8138] is determined by whether it is used in the RPL main DODAG, e.g., by setting the "T" flag [RFC9035] in the RPL configuration option.

The Track Ingress that places a packet in a Track encapsulates it with an IP-in-IP header, a Routing Header, and an IPv6 Hop-by-Hop Option Header that contains the RPL Packet Information (RPI) as follows:

* In the uncompressed form, the source of the packet is the address that this router uses as DODAGID for the Track, the destination is the first Via Address in the NSM-VIO, and the RH is a Source Routing Header (SRH) [RFC6554] that contains the list of the remaining Via Addresses, ending with the Track Egress.

* The preferred alternative in a network where 6LoWPAN Header Compression [RFC6282] is used is to leverage "IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) Paging Dispatch" [RFC8025] to compress the RPL artifacts as indicated in [RFC8138].

  In that case, the source routed header is the exact copy of the (chain of) SRH-6LoRH found in the NSM-VIO, also ending with the Track Egress. The RPI-6LoRH is appended next, followed by an IP-in-IP 6LoRH Header that indicates the Ingress router in the Encapsulator Address field, see as a similar case Figure 20 of [RFC9035].

To signal the Track in the packet, this specification leverages the RPL Forwarding model as follows:

* In the data packets, the Track DODAGID and the TrackID MUST be respectively signaled as the IPv6 Source Address and the RPLInstanceID field of the RPI that MUST be placed in the outer chain of IPv6 Headers.

The RPI carries a local RPLInstanceID called the TrackID, which, in association with the DODAGID, indicates the Track along which the packet is forwarded.

The D flag in the RPLInstanceID MUST be set to 0 to indicate that the source address in the IPv6 header is set to the DODAGID (more in Section 6.3).

* This draft conforms to the principles of [RFC9008] with regards to packet forwarding and encapsulation along a Track, as follows:

  - With this draft, the Track is a RPL DODAG. From the perspective of that DODAG, the Track Ingress is the Root, the Track Egress is a RPL-Aware 6LR, and neighbors of the Track Egress that can be reached via the Track, but are external to it, are external destinations and treated as RPL-Unaware Leaves (RULs). The encapsulation rules in [RFC9008] apply.

  - If the Track Ingress is the originator of the packet and the Track Egress is the destination of the packet, there is no need for an encapsulation.

  - So the Track Ingress must encapsulate the traffic that it did not originate, and it must include an RPI in the encapsulation to signal the TrackID.

  A packet that is being routed over the RPL Instance associated to a first Non-Storing Mode Track MAY be placed recursively in a second Track to cover one loose hop of the first Track as discussed in more details Section 3.5.2.3. On the other hand, a Storing Mode Segment must be strict and a packet that it placed in a Storing Mode Segment MUST follow that Segment till the Segment Egress.

It is known that a packet is forwarded along a Track by the source address and the RPI in the encapsulation. The Track ID is used to identify the RIB entries associated to that Track, which, in intermediate nodes, correspond to the P-routes for the segments of the Track that the forwarding router is aware of. The packet processing uses a precedence that favors self delivery or routing header handling when one is present, then delivery to direct neighbors, then to indirect neighbors, then routing along a segment along the Track, and finally as a last resort injecting the packet in another Track.

To achieve this, the packet handling logic MUST happen in the following order:

* If the destination of the packet is self:

  1. if the header chain contains a RPL Source Route Header that is not fully consumed, then the packet is forwarded along the Track as prescribed by [RFC6554], meaning that the next entry in the routing header becomes the destination;

  2. otherwise: if the packet was encapsulated, then the packet is decapsulated and the forwarding process recurses; else the packet is delivered to the stack.

* Otherwise, the packet is forwarded as follows:

  1. If the destination of the packet is a direct neighbor, e.g., installed by IPv6 Neighbor Discovery, then the packet the packet MUST be forwarded to that neighbor;

  2. Else If the destination of the packet is an indirect neighbor, e.g., installed by a multicast DAO message from a common neighbor, see Section 4.1.4, then the packet MUST be forwarded to the common neighbor;

  3. Else, if there is a RIB entry for the same Track (e.g., installed by an SM-VIO in a DAO message with the destination as target), and the next hop in the RIB entry is a direct neighbor, then the packet is passed to that neighbor;

  4. Else, if there is a RIB entry for the different Track (e.g., installed by an NSM-VIO in a DAO message with the destination as target), then the packet is encapsulated to be forwarded along that Track and the forwarding process recurses; otherwise the packet is dropped.

  5. To avoid loops, and as opposed to packets that were not encapsulated, a packet that was decapsulated from a Track MUST NOT be routed along the default route of the main DODAG; this would mean that the end-to-end path is uncontrolled. The node that discovers the fault MUST discard the packet.

The node that drops a packet for either of the reasons above MUST send an ICMPv6 Error message [RFC4443] to the Root, with a new Code "Error in P-Route" (See Section 11.15). The Root can then repair by updating the broken Segment and/or Tracks, and in the case of a broken Segment, remove the leftover sections of the Segment using SM-VIOs with a lifetime of 0 indicating the section to one or more nodes being removed (See Section 6.6).

In case of a permanent forwarding error along a Source Route path, the node that fails to forward SHOULD send an ICMP error with a code "Error in Source Routing Header" back to the source of the packet, as described in section 11.2.2.3. of [RPL]. Upon receiving this message, the encapsulating node SHOULD stop using the source route path for a reasonable period of time which depends on the deployment, and it SHOULD send an ICMP message with a Code "Error in P-Route" to the Root. Failure to follow these steps may result in packet loss and wasted resources along the source route path that is broken.

Either way, the ICMP message MUST be throttled in case of consecutive occurrences. It MUST be sourced at the ULA or a GUA that is used in this Track for the source node, so the Root can establish where the error happened.

The portion of the invoking packet that is sent back in the ICMP message SHOULD record at least up to the RH if one is present, and this hop of the RH SHOULD be consumed by this node so that the destination in the IPv6 header is the next hop that this node could not reach. If a 6LoWPAN Routing Header (6LoRH) [RFC8138] is used to carry the IPv6 routing information in the outer header then that whole 6LoRH information SHOULD be present in the ICMP message.

6.8. Compression of the RPL Artifacts

When using [RFC8138] in the main DODAG operated in Non-Storing Mode in a 6LoWPAN LLN, a typical packet that circulates in the main DODAG is formatted as shown in Figure 20, representing the case where an IPv6-in-IPv6 encapsulation is needed (see Table 19 of [RFC9008]):

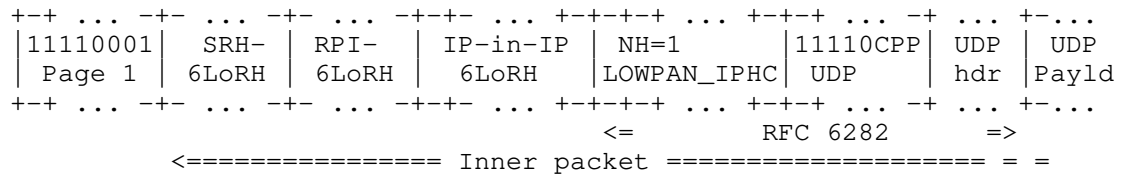


Figure 20: A Packet as Forwarded along the main DODAG

Since there is no page switch between the encapsulated packet and the encapsulation, the first octet of the compressed packet that acts as page selector is actually removed at encapsulation, so the inner packet used in the descriptions below starts with the SRH-6LoRH, and is exactly the packet represented in Figure 20, from the second octet onward.

When encapsulating that inner packet to place it in the Track, the first header that the Ingress appends at the head of the inner packet is an IP-in-IP 6LoRH Header; in that header, the encapsulator address, which maps to the IPv6 source address in the uncompressed form, contains a GUA or ULA IPv6 address of the Ingress node that serves as DODAG ID for the Track, expressed in the compressed form and using the DODAGID of the main DODAG as compression reference. If the address is compressed to 2 bytes, the resulting value for the Length field shown in Figure 21 is 3, meaning that the SRH-6LoRH as a whole is 5-octets long.

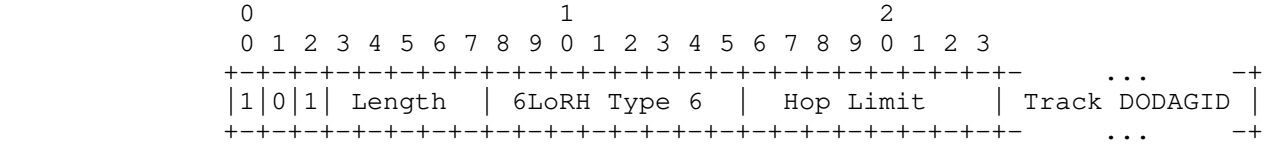


Figure 21: The IP-in-IP 6LoRH Header

At the head of the resulting sequence of bytes, the track Ingress then adds the RPI that carries the TrackID as RPLinstanceID as a P-RPI-6LoRH Header, as illustrated in Figure 12, using the TrackID as RPLInstanceID. Combined with the IP-in-IP 6LoRH Header, this allows to identify the Track without ambiguity.

The SRH-6LoRH is then added at the head of the resulting sequence of bytes as a verbatim copy of the content of the SR-VIO that signaled the selected lane.

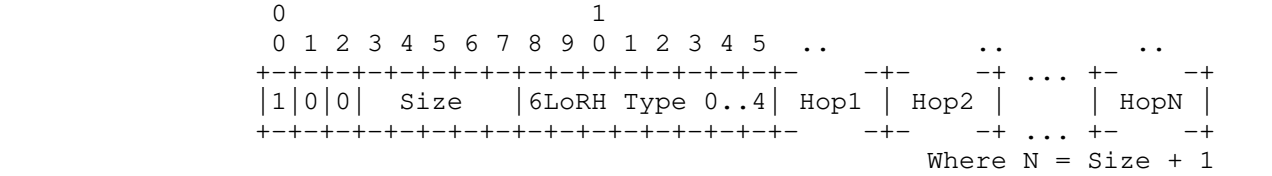


Figure 22: The SRH 6LoRH Header

The format of the resulting encapsulated packet in [RFC8138] compressed form is illustrated in Figure 23:

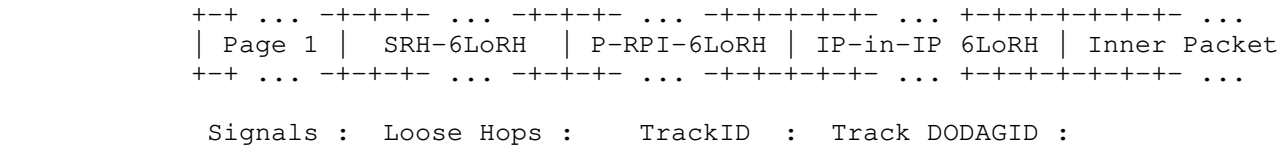


Figure 23: A Packet as Forwarded along a Track

7. Lesser Constrained Variations

7.1. Storing Mode main DODAG

This specification expects that the main DODAG is operated in Non-Storing Mode. The reasons for that limitation are mostly related to LLN operations, power and spectrum conservation:

* In Non-Storing Mode, the Root already knowns the DODAG topology, so the additional topological information is reduced to the siblings.

* The downward routes are updated with unicast messages to the Root, which ensures that the Root can reach back to the LLN nodes after a repair faster than in the case of Storing Mode. Also the Root can control the use of the path diversity in the DODAG to reach the LLN nodes. For both reasons, Non-Storing Mode provides better capabilities for the Root to maintain the P-Routes.

* When the main DODAG is operated in Non-Storing Mode, P-Routes enable loose Source Routing, which is only an advantage in that mode. Storing Mode does not use Source Routing Headers, and does not derive the same benefits from this capability.

On the other hand, since RPL is a Layer-3 routing protocol, its applicability extends beyond LLNs to a generic IP network. RPL requires less resources than alternative IGPs like OSPF, ISIS, EIGRP, BABEL or RIP at the expense of a route stretch vs. the shortest path routes to a destination that those protocols compute. P-Routes add the capability to install shortest and/or constrained routes to special destinations such as discussed in section A.9.4. of the ANIMA ACP [RFC8994].

In a powered and wired network, when enough memory to store the needed routes is available, the RPL Storing Mode proposes a better trade-off than the Non-Storing, as it reduces the route stretch and lowers the load on the Root. In that case, the control path between the Root and the LLN nodes is highly available compared to LLNs, and the nodes can be reached to maintain the P-Routes at most times.

This section specifies the additions that are needed to support Projected Routes when the main DODAG is operated in Storing Mode. As long as the RPI can be processed adequately by the dataplane, the changes to this specification are limited to the DAO message. The Track structure, routes and forwarding operations remain the same. Since there is no capability negotiation, the expectation is that all the nodes in the network support this specification in the same fashion, or are configured the same way through management.

In Storing Mode, the Root misses the Child to Parent relationship that forms the main DODAG, as well as the sibling information. To provide that knowledge the nodes in the network MUST send additional DAO messages that are unicast to the Root just like Non-Storing DAO messages are.

In the DAO message, the originating router advertises a set of neighbor nodes using Sibling Information Options (SIO)s, regardless of the relative position in the DODAG of the advertised node vs. this router.

The DAO message MUST be formed as follows:

* The originating router is identified by the source address of the DAO. That address MUST be the one that this router registers to neighbor routers so the Root can correlate the DAOs from those routers when they advertise this router as their neighbor. The DAO contains one or more sequences of one Transit Information Option and one or more Sibling Information Options. There is no RPL Target Option so the Root is not confused into adding a Storing Mode route to the Target.

* The TIO is formed as in Storing Mode, and the Parent Address is not present. The Path Sequence and Path Lifetime fields are aligned with the values used in the Address Registration of the node(s) advertised in the SIO, as explained in Section 9.1. of [RFC9010]. Having similar values in all nodes allows factorising the TIO for multiple SIOs as done with [RPL].

* The TIO is followed by one or more SIOs that provide an address (ULA or GUA) of the advertised neighbor node.

But the RPL routing information headers may not be supported on all type of routed network infrastructures, especially not in high-speed routers. When the RPI is not supported in the dataplane, there cannot be local RPL Instances and RPL can only operate as a single topology (the main DODAG). The RPL Instance is that of the main DODAG and the Ingress node that encapsulates is not the Root. The routes along the Tracks are alternate routes to those available along the main DODAG. They MAY conflict with routes to children and MUST take precedence in the routing table. The Targets MUST be adjacent to the Track Egress to avoid loops that may form if the packet is reinjected in the main DODAG.

7.2. A Track as a Full DODAG

This specification builds parallel or crossing Track Lanes as opposed to a more complex DODAG with interconnections at any place desirable. The reason for that limitation is related to constrained node operations, and the capability to store large amount of topological information and compute complex paths:

* With this specification, the node in the LLN has no topological awareness, and does not need to maintain dynamic information about the link quality and availability.

* The Root has a complete topological information and statistical metrics that allow it or its PCE to perform a global optimization of all Tracks in its DODAG. Based on that information, the Root computes the lane and produces the source route paths.

* The node merely selects one of the proposed paths and applies the associated pre-computed routing header in the encapsulation. This alleviates both the complexity of computing a path and the compressed form of the routing header.

The RAW Architecture [RAW-ARCHI] actually expects the PLR at the Track Ingress to react to changes in the forwarding conditions along the Track, and reroute packets to maintain the required degree of reliability. To achieve this, the PLR needs the full richness of a DODAG to form any path that could meet the Service Level Objective (SLO).

This section specifies the additions that are needed to turn the Track into a full DODAG and enable the main Root to provide the necessary topological information to the Track Ingress. The expectation is that the metrics that the PLR uses are of an order other than that of the PCE, because of the difference of time scale between routing and forwarding, more in [RAW-ARCHI]. It follows that the PLR will learn the metrics it needs from an alternate source, e.g., OAM frames.

To pass the topological information to the Ingress, the Root uses a P-DAO messages that contains sequences of Target and Transit Information options that collectively represent the Track, expressed in the same fashion as in classical Non-Storing Mode. The difference is that the Root is the source as opposed to the destination, and can report information on many Targets, possibly the full Track, with one P-DAO.

Note that the Path Sequence and Lifetime in the TIO are selected by the Root, and that the Target/Transit information tuples in the P-DAO are not those received by the Root in the DAO messages about the said Targets. The Track may follow sibling routes and does not need to be congruent with the main DODAG.

8. Profiles

This document provides a set of tools that may or may not be needed by an implementation depending on the type of application it serves. This sections described profiles that can be implemented separately and can be used to discriminate what an implementation can and cannot do. This section describes profiles that enable implementing only a portion of this specification to meet a particular use case.

Profiles 0 to 2 operate in the main Instance and do not require the support of local RPL Instances or the indication of the RPL Instance in the data plane. Profile 3 and above leverage Local RPL Instances to build arbitrary Tracks Rooted at the Track Ingress and using its namespace for TrackID.

Profiles 0 and 1 are REQUIRED by all implementations that may be used in LLNs; Profile 1 leverages Storing Mode to reduce the size of the Source Route Header in the most common LLN deployments. Profile 2 is RECOMMENDED in high speed / wired environment to enable traffic Engineering and network automation. All the other profile / environment combinations are OPTIONAL.

Profile 0 Profile 0 is the Legacy support of [RPL] Non-Storing Mode, with default routing Northwards (up) and strict source routing Southwards (down the main DODAG). It provides the minimal common functionality that must be implemented as a prerequisite to all the Track-supporting profiles. The other Profiles extend Profile 0 with selected capabilities that this specification introduces on top.

Profile 1 (Storing Mode P-Route Segments along the main DODAG) Profile 1 does not create new paths; compared to Profile 0, it combines Storing and Non-Storing Modes to balance the size of the Routing Header in the packet and the amount of state in the intermediate routers in a Non-Storing Mode RPL DODAG.

Profile 2 (Non-Storing Mode P-Route Segments along the main DODAG) Profile 2 extends Profile 0 with Strict Source-Routing Non-Storing Mode P-Routes along the main DODAG, which is the same as Profile 1 but using NSM VIOs as opposed to SM VIOs. Profile 2 provides the same capability to compress the SRH in packets down the main DODAG as Profile 1, but it requires an encapsulation, in order to insert

an additional SRH between the loose source routing hops. In that case, the Tracks MUST be installed as subTracks of the main DODAG, the main Instance MUST be used as TrackID. Note that the Ingress node encapsulates but is not the Root, as it does not own the DODAGID.

Profile 3 In order to form the best path possible, this Profile requires the support of Sibling Information Option to inform the Root of additional possible hops. Profile 3 extends Profile 1 with additional Storing Mode P-Routes that install Segments that do not follow the main DODAG. If the Segment Ingress (in the SM-VIO) is the same as the IPv6 Address of the Track Ingress (in the projected DAO base Object), the P-DAO creates an implicit Track between the Segment Ingress and the Segment Egress.

Profile 4 Profile 4 extends Profile 2 with Strict Source-Routing Non-Storing Mode P-Routes to form forward Tracks that are inside the main DODAG but do not necessarily follow it. A Track is formed as one or more strict source routed paths between the Root that is the Track Ingress, and the Track Egress that is the last node.

Profile 5 Profile 5 Combines Profile 4 with Profile 1 and enables loose source routing between the Ingress and the Egress of the Track. As in Profile 1, Storing Mode P-Routes form the connections in the loose source route.

Profile 6 Profile 6 Combines Profile 4 with Profile 2 and also enables loose source routing between the Ingress and the Egress of the Track.

Profile 7 Profile 7 implements Profile 5 in a main DODAG that is operated in Storing Mode as presented in Section 7.1. As in Profile 1 and 2, the TrackID is the RPLInstanceID of the main DODAG. Longest match rules decide whether a packet is sent along the main DODAG or rerouted in a track.

Profile 8 Profile 8 is offered in preparation of the RAW work, and for use cases where an arbitrary node in the network can afford the same code complexity as the RPL Root in a traditional deployment. It offers a full DODAG visibility to the Track Ingress as specified in Section 7.2 in a Non-Storing Mode main DODAG.

Profile 9 Profile 9 combines profiles 7 and 8, operating the Track as a full DODAG within a Storing Mode main DODAG, using only the main DODAG RPLInstanceID as TrackID.

9. Backwards Compatibility

This specification can operate in a mixed network where some nodes support it and some do not. There are restrictions, though. All nodes that need to process a P-DAO MUST support this specification. As discussed in Section 3.7.1, how the root knows the node capabilities and whether they support this specification is out of scope.

This specification defines the 'D' flag in the RPL DODAG Configuration Option (see Section 4.1.7) to signal that the RPL nodes can request the creation of Tracks. The requester may not know whether the Track can effectively be constructed, and whether enough nodes along the preferred paths support this specification. Therefore, it makes sense to only set the 'D' flags in the DIO when the conditions of success are in place, in particular when all the nodes that could be on the path of tracks are upgraded.

10. Security Considerations

It is worth noting that with [RPL], every node in the LLN is RPL-aware and can inject any RPL-based attack in the network. This draft uses messages that are already present in RPL [RPL] with optional secured versions. The same secured versions may be used with this draft, and whatever security is deployed for a given network also applies to the flows in this draft.

The LLN nodes depend on the 6LBR and the RPL participants for their operation. A trust model is necessary to ensure that the right devices are acting in these roles, so as to avoid threats such as black-holing, (see [RFC7416] section 7). This trust model could be at a minimum based on a Layer-2 Secure joining and the Link-Layer security. This is a generic 6LoWPAN requirement, see Req5.1 in Appendix B.5 of [RFC8505].

In a general manner, the Security Considerations in [RPL], and [RFC7416] apply to this specification as well. The Link-Layer security is needed in particular to prevent Denial-Of-Service attacks whereby a rogue router creates a high churn in the RPL network by constantly injecting forged P-DAO messages and using up all the available storage in the attacked routers.

With this specification, only the Root may generate P-DAO messages. PDR messages may only be sent to the Root. This specification expects that the communication with the Root is authenticated but does not enforce which method is used.

Additionally, the trust model could include a role validation (e.g., using a role-based authorization) to ensure that the node that claims to be a RPL Root is entitled to do so. That trust should propagate from Egress to Ingress in the case of a Storing Mode P-DAO.

This specification suggests some validation of the VIO to prevent basic loops by avoiding that a node appears twice. But that is only a minimal protection. Arguably, an attacker that can inject P-DAOs can reroute any traffic and deplete critical resources such as spectrum and battery in the LLN rapidly.

11. IANA Considerations

11.1. RPL DODAG Configuration Option Flag

IANA is requested to assign a flag from the "DODAG Configuration Option Flags for MOP 0..6" [RFC9010] registry under the heading "Routing Protocol for Low Power and Lossy Networks (RPL)" as follows:

Bit Number	Capability Description	Reference
0 (suggested)	Projected Routes Support (D)	THIS RFC

Table 21: New DODAG Configuration Option Flag

IANA is requested to add [THIS RFC] as a reference for MOP 7 in the RPL Mode of Operation registry.

11.2. Elective 6LoWPAN Routing Header Type

IANA is requested to update the "Elective 6LoWPAN Routing Header Type" registry that was created for [RFC8138] under the heading "Elective 6LoWPAN Routing Header Type" in [IANA-6LO] and assign the following value:

Value	Description	Reference
8 (Suggested)	P-RPI-6LoRH	THIS RFC

Table 22: New Elective 6LoWPAN Routing Header Type

11.3. Critical 6LoWPAN Routing Header Type

IANA is requested to update the "Critical 6LoWPAN Routing Header Type" registry that was created for [RFC8138] under the heading "Critical 6LoWPAN Routing Header Type" in [IANA-6LO] and assign the following value:

Value	Description	Reference
8 (Suggested)	P-RPI-6LoRH	THIS RFC

Table 23: New Critical 6LoWPAN Routing Header Type

11.4. Registry For The RPL Option Flags

IANA is requested to create a registry for the 8-bit "RPL Option Flags" field, as detailed in Figure 11, under the heading "Routing Protocol for Low Power and Lossy Networks (RPL)". The bits are indexed from 0 (leftmost) to 7. Each bit is tracked with the following qualities:

* Bit number (counting from bit 0 as the most significant bit)

* Indication When Set

* Reference

Registration procedure is "Standards Action" [RFC8126]. The initial allocation is as indicated in Table 24:

Bit number	Indication When Set	Reference
0	Down 'O'	[RFC6553]
1	Rank-Error (R)	[RFC6553]
2	Forwarding-Error (F)	[RFC6553]
3 (Suggested)	Projected-Route (P)	THIS RFC
4..255	Unassigned	

Table 24: Initial PDR Flags

11.5. RPL Control Codes

IANA is requested to update the "RPL Control Codes" registry under the heading "Routing Protocol for Low Power and Lossy Networks (RPL)" as indicated in Table 25:

Code	Description	Reference
0x09 (Suggested)	Projected DAO Request (PDR)	THIS RFC
0x0A (Suggested)	PDR-ACK	THIS RFC

Table 25: New RPL Control Codes

11.6. RPL Control Message Options

IANA is requested to update the "RPL Control Message Options" registry under the heading "Routing Protocol for Low Power and Lossy Networks (RPL)" as indicated in Table 26:

Value	Meaning	Reference
0x0E (Suggested)	Stateful VIO (SM-VIO)	THIS RFC
0x0F (Suggested)	Source-Routed VIO (NSM-VIO)	THIS RFC
0x10 (Suggested)	Sibling Information option	THIS RFC

Table 26: RPL Control Message Options

11.7. SubRegistry for the Projected DAO Request Flags

IANA is requested to create a registry for the 8-bit "Projected DAO Request (PDR)" field under the heading "Routing Protocol for Low Power and Lossy Networks (RPL)". The bits are indexed from 0 (leftmost) to 7. Each bit is tracked with the following qualities:

* Bit number (counting from bit 0 as the most significant bit)

* Capability description

* Reference

Registration procedure is "Standards Action" [RFC8126]. The initial allocation is as indicated in Table 27:

Bit number	Capability description	Reference
0	PDR-ACK request (K)	THIS RFC
1	Requested path should be redundant (R)	THIS RFC
2..255	Unassigned	

Table 27: Initial PDR Flags

11.8. SubRegistry for the PDR-ACK Flags

IANA is requested to create a registry for the 8-bit "PDR-ACK Flags" field under the heading "Routing Protocol for Low Power and Lossy Networks (RPL)". The bits are indexed from 0 (leftmost) to 7. Each bit is tracked with the following qualities:

* Bit number (counting from bit 0 as the most significant bit)

* Capability description

* Reference

Registration procedure is "Standards Action" [RFC8126]. No bit is currently assigned for the PDR-ACK Flags.

11.9. Registry for the PDR-ACK Acceptance Status Values

IANA is requested to create a registry for the 8-bit "PDR-ACK Acceptance Status Values" under the heading "Routing Protocol for Low Power and Lossy Networks (RPL)". Each value is tracked with the following qualities:

* Value

* Meaning

* Reference

the possible values are expressed as a 6-bit unsigned integer (0..63). the registration procedure is "Standards Action" [RFC8126].

The (suggected) initial allocation is as indicated in Table 28:

Value	Meaning	Reference
0	Unqualified Acceptance	THIS RFC
1..63	Unassigned	

Table 28: Acceptance values of the PDR-ACK Status

11.10. Registry for the PDR-ACK Rejection Status Values

IANA is requested to create a registry for the 6-bit "PDR-ACK Rejection Status Values" under the heading "Routing Protocol for Low Power and Lossy Networks (RPL)". Each value is tracked with the following qualities:

* Value
* Meaning
* Reference

the possible values are expressed as a 6-bit unsigned integer (0..63). the registration procedure is "Standards Action" [RFC8126].

The (suggected) initial allocation is as indicated in Table 29:

Value	Meaning	Reference
0	Unqualified Rejection	THIS RFC
1	Transient Failure	THIS RFC
2..63	Unassigned	

Table 29: Rejection values of the PDR-ACK Status

11.11. SubRegistry for the Via Information Options Flags

IANA is requested to create a registry for the 8-bit "Via Information Options (VIO) Flags" field under the heading "Routing Protocol for Low Power and Lossy Networks (RPL)". The bits are indexed from 0 (leftmost) to 7. Each bit is tracked with the following qualities:

* Bit number (counting from bit 0 as the most significant bit)

* Capability description

* Reference

Registration procedure is "Standards Action" [RFC8126]. No bit is currently assigned for the VIO Flags, more in Section 5.3.

11.12. SubRegistry for the Sibling Information Option Flags

IANA is requested to create a registry for the 5-bit "Sibling Information Option (SIO) Flags" field under the heading "Routing Protocol for Low Power and Lossy Networks (RPL)". The bits are indexed from 0 (leftmost) to 4. Each bit is tracked with the following qualities:

* Bit number (counting from bit 0 as the most significant bit)

* Capability description

* Reference

Registration procedure is "Standards Action" [RFC8126]. The initial allocation is as indicated in Table 30, more in Figure 17:

Bit number	Capability description	Reference
0 (Suggested)	"S" flag: Sibling in same DODAG as Self	THIS RFC
1..4	Unassigned	

Table 30: Initial SIO Flags

11.13. Destination Advertisement Object Flag

IANA is requested to update the "Destination Advertisement Object (DAO) Flags" registry created in Section 20.11 of [RPL] under the heading "Routing Protocol for Low Power and Lossy Networks (RPL)" as indicated in Table 31, more in Section 4.1.1:

Bit Number	Capability Description	Reference
2 (Suggested)	Projected DAO (P)	THIS RFC

Table 31: New Destination Advertisement Object (DAO) Flag

11.14. Destination Advertisement Object Acknowledgment Flag

IANA is requested to update the "Destination Advertisement Object (DAO) Acknowledgment Flags" registry created in Section 20.12 of [RPL] under the heading "Routing Protocol for Low Power and Lossy Networks (RPL)" as indicated in Table 32, more in Section 4.1.2:

Bit Number	Capability Description	Reference
1 (Suggested)	Projected DAO-ACK (P)	THIS RFC

Table 32: New Destination Advertisement Object Acknowledgment Flag

11.15. New ICMPv6 Error Code

In some cases RPL will return an ICMPv6 error message when a message cannot be forwarded along a P-Route.

This specification requires that a new code is allocated from the 'ICMPv6 "Code" Fields' heading of the "Internet Control Message Protocol version 6 (ICMPv6) Parameters" Registry for "Type 1 - Destination Unreachable", with a suggested code value of 9, to be confirmed by IANA to indicate an "Error in P-Route".

11.16. RPL Rejection Status values

IANA is requested to update the "RPL Rejection Status" registry under the heading "Routing Protocol for Low Power and Lossy Networks (RPL)" as indicated in Table 33:

Value	Meaning	Reference
2 (Suggested)	Out of Resources	THIS RFC
3 (Suggested)	Error in VIO	THIS RFC
4 (Suggested)	Predecessor Unreachable	THIS RFC
5 (Suggested)	Unreachable Target	THIS RFC
6..63	Unassigned	

Table 33: Rejection values of the RPL Status

12. Acknowledgments

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13. Normative References

[INT-ARCHI] Braden, R., Ed., "Requirements for Internet Hosts - Communication Layers", STD 3, RFC 1122, DOI 10.17487/RFC1122, October 1989, <https://www.rfc-editor.org/info/rfc1122>.

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

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

[RFC6282] Hui, J., Ed. and P. Thubert, "Compression Format for IPv6 Datagrams over IEEE 802.15.4-Based Networks", RFC 6282, DOI 10.17487/RFC6282, September 2011, <https://www.rfc-editor.org/info/rfc6282>.

[RPL] Winter, T., Ed., Thubert, P., Ed., Brandt, A., Hui, J., Kelsey, R., Levis, P., Pister, K., Struik, R., Vasseur, JP., and R. Alexander, "RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks", RFC 6550, DOI 10.17487/RFC6550, March 2012, <https://www.rfc-editor.org/info/rfc6550>.

[RFC6553] Hui, J. and JP. Vasseur, "The Routing Protocol for Low-Power and Lossy Networks (RPL) Option for Carrying RPL Information in Data-Plane Datagrams", RFC 6553, DOI 10.17487/RFC6553, March 2012, <https://www.rfc-editor.org/info/rfc6553>.

[RFC6554] Hui, J., Vasseur, JP., Culler, D., and V. Manral, "An IPv6 Routing Header for Source Routes with the Routing Protocol for Low-Power and Lossy Networks (RPL)", RFC 6554, DOI 10.17487/RFC6554, March 2012, <https://www.rfc-editor.org/info/rfc6554>.

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

[RFC8138] Thubert, P., Ed., Bormann, C., Toutain, L., and R. Cragie, "IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) Routing Header", RFC 8138, DOI 10.17487/RFC8138, April 2017, <https://www.rfc-editor.org/info/rfc8138>.

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

[RFC8754] Filsfils, C., Ed., Dukes, D., Ed., Previdi, S., Leddy, J., Matsushima, S., and D. Voyer, "IPv6 Segment Routing Header (SRH)", RFC 8754, DOI 10.17487/RFC8754, March 2020, <https://www.rfc-editor.org/info/rfc8754>.

[RFC9008] Robles, M.I., Richardson, M., and P. Thubert, "Using RPI Option Type, Routing Header for Source Routes, and IPv6-in-IPv6 Encapsulation in the RPL Data Plane", RFC 9008, DOI 10.17487/RFC9008, April 2021, <https://www.rfc-editor.org/info/rfc9008>.

[RFC9030] Thubert, P., Ed., "An Architecture for IPv6 over the Time-Slotted Channel Hopping Mode of IEEE 802.15.4 (6TiSCH)", RFC 9030, DOI 10.17487/RFC9030, May 2021, <https://www.rfc-editor.org/info/rfc9030>.

[RAW-ARCHI] Thubert, P., "Reliable and Available Wireless Architecture", Work in Progress, Internet-Draft, draft-ietf-raw-architecture-16, 20 October 2023, <https://datatracker.ietf.org/doc/html/draft-ietf-raw-architecture-16>.

14. Informative References

[RFC4655] Farrel, A., Vasseur, J.-P., and J. Ash, "A Path Computation Element (PCE)-Based Architecture", RFC 4655, DOI 10.17487/RFC4655, August 2006, <https://www.rfc-editor.org/info/rfc4655>.

[RFC4861] Narten, T., Nordmark, E., Simpson, W., and H. Soliman, "Neighbor Discovery for IP version 6 (IPv6)", RFC 4861, DOI 10.17487/RFC4861, September 2007, <https://www.rfc-editor.org/info/rfc4861>.

[6LoWPAN] Montenegro, G., Kushalnagar, N., Hui, J., and D. Culler, "Transmission of IPv6 Packets over IEEE 802.15.4 Networks", RFC 4944, DOI 10.17487/RFC4944, September 2007, <https://www.rfc-editor.org/info/rfc4944>.

[RFC5440] Vasseur, JP., Ed. and JL. Le Roux, Ed., "Path Computation Element (PCE) Communication Protocol (PCEP)", RFC 5440, DOI 10.17487/RFC5440, March 2009, <https://www.rfc-editor.org/info/rfc5440>.

[RFC6997] Goyal, M., Ed., Baccelli, E., Philipp, M., Brandt, A., and J. Martocci, "Reactive Discovery of Point-to-Point Routes in Low-Power and Lossy Networks", RFC 6997, DOI 10.17487/RFC6997, August 2013, <https://www.rfc-editor.org/info/rfc6997>.

[RFC7102] Vasseur, JP., "Terms Used in Routing for Low-Power and Lossy Networks", RFC 7102, DOI 10.17487/RFC7102, January 2014, <https://www.rfc-editor.org/info/rfc7102>.

[RFC7416] Tsao, T., Alexander, R., Dohler, M., Daza, V., Lozano, A., and M. Richardson, Ed., "A Security Threat Analysis for the Routing Protocol for Low-Power and Lossy Networks (RPLs)", RFC 7416, DOI 10.17487/RFC7416, January 2015, <https://www.rfc-editor.org/info/rfc7416>.

[RFC8025] Thubert, P., Ed. and R. Cragie, "IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) Paging Dispatch", RFC 8025, DOI 10.17487/RFC8025, November 2016, <https://www.rfc-editor.org/info/rfc8025>.

[RFC8402] Filsfils, C., Ed., Previdi, S., Ed., Ginsberg, L., Decraene, B., Litkowski, S., and R. Shakir, "Segment Routing Architecture", RFC 8402, DOI 10.17487/RFC8402, July 2018, <https://www.rfc-editor.org/info/rfc8402>.

[RFC8505] Thubert, P., Ed., Nordmark, E., Chakrabarti, S., and C. Perkins, "Registration Extensions for IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) Neighbor Discovery", RFC 8505, DOI 10.17487/RFC8505, November 2018, <https://www.rfc-editor.org/info/rfc8505>.

[RFC8655] Finn, N., Thubert, P., Varga, B., and J. Farkas, "Deterministic Networking Architecture", RFC 8655, DOI 10.17487/RFC8655, October 2019, <https://www.rfc-editor.org/info/rfc8655>.

[RFC8930] Watteyne, T., Ed., Thubert, P., Ed., and C. Bormann, "On Forwarding 6LoWPAN Fragments over a Multi-Hop IPv6 Network", RFC 8930, DOI 10.17487/RFC8930, November 2020, <https://www.rfc-editor.org/info/rfc8930>.

[RFC8931] Thubert, P., Ed., "IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) Selective Fragment Recovery", RFC 8931, DOI 10.17487/RFC8931, November 2020, <https://www.rfc-editor.org/info/rfc8931>.

[RFC8994] Eckert, T., Ed., Behringer, M., Ed., and S. Bjarnason, "An Autonomic Control Plane (ACP)", RFC 8994, DOI 10.17487/RFC8994, May 2021, <https://www.rfc-editor.org/info/rfc8994>.

[RFC9010] Thubert, P., Ed. and M. Richardson, "Routing for RPL (Routing Protocol for Low-Power and Lossy Networks) Leaves", RFC 9010, DOI 10.17487/RFC9010, April 2021, <https://www.rfc-editor.org/info/rfc9010>.

[RFC9035] Thubert, P., Ed. and L. Zhao, "A Routing Protocol for Low-Power and Lossy Networks (RPL) Destination-Oriented Directed Acyclic Graph (DODAG) Configuration Option for the 6LoWPAN Routing Header", RFC 9035, DOI 10.17487/RFC9035, April 2021, <https://www.rfc-editor.org/info/rfc9035>.

[RFC9450] Bernardos, CJ., Ed., Papadopoulos, G., Thubert, P., and F. Theoleyre, "Reliable and Available Wireless (RAW) Use Cases", RFC 9450, DOI 10.17487/RFC9450, August 2023, <https://www.rfc-editor.org/info/rfc9450>.

[I-D.kuehlewind-update-tag] Kühlewind, M. and S. Krishnan, "Definition of new tags for relations between RFCs", Work in Progress, Internet-Draft, draft-kuehlewind-update-tag-04, 12 July 2021, <https://datatracker.ietf.org/doc/html/draft-kuehlewind-update-tag-04>.

[I-D.irtf-panrg-path-properties] Enghardt, R. and C. Krähenbühl, "A Vocabulary of Path Properties", Work in Progress, Internet-Draft, draft-irtf-panrg-path-properties-08, 6 March 2023, <https://datatracker.ietf.org/doc/html/draft-irtf-panrg-path-properties-08>.

[PCE] IETF, "Path Computation Element", <https://dataTracker.ietf.org/doc/charter-ietf-pce/>.

[IANA-6LO] IETF, "IPv6 Low Power Personal Area Network Parameters", <https://www.iana.org/assignments/_6lowpan-parameters/_6lowpan-parameters.xhtml>.

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Controlling Secure Network Enrollment in RPL networks
draft-ietf-roll-enrollment-priority-10

Abstract

[RFC9032] defines a method by which a potential [RFC9031] enrollment proxy can announce itself as available for new Pledges to enroll on a network. The announcement includes a priority for enrollment. This document provides a mechanism by which a RPL DODAG Root can globally disable enrollment announcements or adjust the base priority for enrollment operations.

Status of This Memo

This Internet-Draft is submitted in full conformance with the provisions of BCP 78 and BCP 79.

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1. Introduction

[RFC7554] describes the use of the time-slotted channel hopping (TSCH) mode of [ieee802154]. [RFC9031] and [RFC9032] describe mechanisms by which a new node (the "pledge") can use a friendly router as a Join Proxy. [RFC9032] describes an extension to the 802.15.4 Enhanced Beacon that is used by a Join Proxy to announce its existence such that Pledges can find them.

1.1. Motivation and Overview

It has become clear that not every routing member of the mesh ought to announce itself as a _Join Proxy_. There are a variety of local reasons for which a 6LR might not want to provide the _Join Proxy_ function. They include low available battery power, already high committed network bandwidth, and little free memory for Neighbor Cache Entry (NCE) slots. (An NCE entry is needed in order to maintain communication with the pledge.)

There are other situations where the operator of the network would like to selectively enable or disable the enrollment process in a specific DODAG. In particular, as the enrollment process involves permitting unencrypted traffic into the best effort part of a network, it would be better to have the enrollment process off when no new nodes are expected.

This document describes a RPL DIO option that can be used to set a minimum enrollment priority. The minimum priority expresses the (lack of) willingness by the RPL DODAG globally to accept new joins. It may derive from multiple constraining factors, for instance, the size of the DODAG, the occupancy of the bandwidth at the DODAG Root, the memory capacity at the Root, or an administrative decision. Each potential _Join Proxy_ utilizes this value as a base on which to add values relating to local conditions, such as its Rank and number of pending joins. As explained in [RFC9032], higher values decrease the likelihood of an unenrolled node sending enrollment traffic via this _Join Proxy_. In particular, by setting the minimum enrollment priority to the maximum value allowed, a network operator can globally disable all new enrollment traffic.

Moreover, when a RPL domain is composed of multiple DODAGs, a node at the edge of more than one such DODAG may not only join any of the DODAGs but also move between them in order to keep their relative sizes balanced. For this, the approximate knowledge of the size of the DODAGs is also an essential metric. Depending on the network policy, the size of the DODAG may or may not affect the minimum enrollment priority. Therefore, since making one proportional to the other would be limiting their value, the current size of the DODAG is advertised separately in the new option.

Updates to the option propagate through the network according to the trickle algorithm. The contents of the option are generated at the DODAG Root and do not change at any hop. If the contents represent an update that is considered important (e.g., quickly disabling any enrollments), the option can trigger trickle timer resets at the nodes to speed up its propagation.

2. Terminology

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.

The term (1)"Join" has been used in documents like [RFC9031] to denote the activity of a new node authenticating itself to the network in order to obtain authorization to become a member of the network.

In the context of the [RFC6550] RPL protocol, the term (2)"Join" has an alternative meaning: that of a node (already authenticated to the network, and already authorized to be a member of the network), deciding which part of the RPL DODAG to attach to. This term "Join" has to do with preferred parent selection processes.

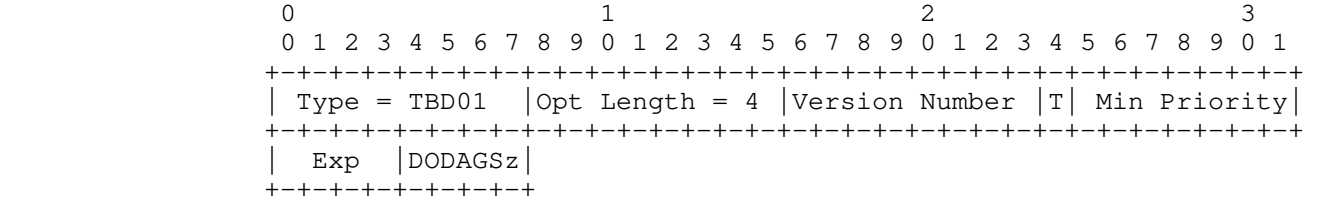
In order to avoid the ambiguity of this term, this document refers to the process (1)"Join" as enrollment, leaving the term "Join" to mean (2)"Join". The term "onboarding" (or "IoT Onboarding") is increasingly used to describe what was called enrollment in other documents. However, the term _Join Proxy_ is retained with its meaning from [RFC9031].

3. Protocol Definition

This document uses the extensions mechanism designed into [RFC6550]. No mechanism is needed to enable it.

3.1. Option Format

The following option is defined for transmission in DIOs issued by the DODAG Root to be propagated within the DODAG.



Type To be assigned by IANA.

Version Number An 8-bit unsigned integer set by the DODAG root and denoting the version number of the contents of the option. The version number is interpreted as a lollipop counter (see Section 7.2 of [RFC6550]).

T A bit indicating whether the particular version of the option is important in that adopting its contents should trigger a trickle timer reset at the node.

Min Priority A 7-bit field providing a base value for the Enhanced

Beacon Join priority. A value of 0x7f (127) disables the _Join Proxy_ function entirely.

Exp A 4-bit unsigned integer indicating the power of 2 that defines the unit of the DODAG Size, such that (unit = 2^Exp).

DODAGSz A 4-bit unsigned integer expressing the size of the DODAG in units that depend on the Exp field. The size of the DODAG is computed as (DODAGSz * 2^Exp).

The size of the DODAG can be measured by the Root based on the DAO activity. In such a case, it represents the number of routes not the number of nodes, and can thus be used to infer the load only in a network where each node advertises roughly the same number of addresses and generates roughly the same amount of traffic. Future work like [I-D.ietf-roll-capabilities] will enable collection of capabilities such as this one in reports to the DODAG Root.

In any case, the DODAG size may slightly change between a DIO and the next, so the value transmitted MUST be considered as an approximation.

3.2. Option Processing

The contents of the option MUST be generated by the DODAG Root. A 6LR MUST NOT change them when propagating the option.

Whenever the DODAG root changes the values of Min Priority or DODAG Size in the option, it MUST also increment the value of Version Number. Moreover, if the change is considered important (i.e., it is expected to propagate in the DODAG quickly), the DODAG Root SHOULD also set the T bit to 1; otherwise, it MUST set the bit to 0.

Upon receiving the option, a 6LR first checks the value of the Version Number field in the option, _vr_, versus the value of the Version Number it has last adopted locally, _vl_.

* If _vl_ is greater than _vr_ (in the lollipop counter order), then the 6LR MUST ignore the received option.

* Otherwise, the 6LR MUST adopt the contents of the option (i.e., the values of Version Number, Min Priority, DODAG Size, and the T bit) as its local ones. Moreover, if _vl_ was smaller than _vr_ (in the lollipop counter order) and the T bit in the received option was set, then the 6LR MUST reset its DIO trickle timer.

A 6LR, which would otherwise be willing to act as a _Join Proxy_, will examine the locally adopted value of Min Priority and to that number add any additional local consideration (such as upstream congestion, number of NCE slots available, etc.).

The maximum resulting value any 6LR can obtain this way is 0x7f.

The resulting priority, if less than 0x7f, should enable the _Join Proxy_ function.

3.3. Upwards Compatibility

A 6LR which did not support this option would not act on it or propagate it in its DIO messages. In effect, the 6LR's children and grandchildren nodes could not receive any telemetry. Therefore, 6LRs that support this option but do not receive it via any path SHOULD assume a default value of 0x40 as their base value for the Enhanced Beacon Join Priority.

A 6LR downstream of a 6LR where there was such an interruption in the telemetry could err in two directions:

* If the value implied by the base value of 0x40 was too low, then the 6LR might continue to attract enrollment traffic when none should have been collected. This is a stressor for the network, but this would also be what would occur without this option at all.

* If the value implied by the base value of 0x40 was too high, then the 6LR might deflect enrollment traffic to other parts of the DODAG, possibly refusing any enrollment traffic at all. In order for this to happen, some significant congestion must be seen in the sub-DODAG where the implied 0x40 was introduced. The 0x40 is only the half-way point, so if such an amount of congestion was present, then this sub-DODAG of the DODAG simply winds up being more cautious than it needed to be.

It is possible that the temporal alternation of the above two situations might introduce cycles of accepting and then rejecting enrollment traffic. This is something an operator should consider if they incrementally deploy this option to an existing LLN. In addition, an operator would be unable to turn off enrollment traffic by sending a maximum value enrollment priority to the sub-DODAG. This situation is unfortunate, but without this option, the the situation would occur all over the DODAG, rather than just in the sub-DODAG that the option did not reach.

4. Security Considerations

As per [RFC7416], RPL control frames either run over a secured layer 2 or use the [RFC6550] Secure DIO methods. This option can be placed into either a "clear" (layer-2 secured) DIO or a layer-3 Secure DIO. As such, this option will have both integrity and confidentiality mechanisms applied to it.

A malicious node that was part of the RPL control plane could see these options and, based upon the observed minimal enrollment priority, could signal a confederate that it was a good time to send malicious join traffic.

Such a malicious node, being already part of the RPL control plane, could also send DIOs with a different minimal enrollment priority, which would cause downstream mesh routers to change their _Join Proxy_ behavior: lower minimal priorities would cause downstream nodes to accept more pledges than the network was expecting; higher minimal priorities could cause the enrollment process to stall.

The use of layer-2 or layer-3 security for RPL control messages prevents the two aforementioned attacks, by preventing malicious nodes from becoming part of the control plane. A node that is attacked and has malware placed on it creates vulnerabilities in the same way such an attack on any node involved in Internet routing protocol does. The rekeying provisions of [RFC9031] exist to permit an operator to remove such nodes from the network easily.

5. Privacy Considerations

There are no new privacy issues caused by this extension.

6. IANA Considerations

Allocate a new number TBD01 from Registry RPL Control Message Options. This entry should be called Minimum Enrollment Priority.

7. Acknowledgements

This has been reviewed by Thomas Watteyne.

8. References

8.1. Normative References

[ieee802154]
IEEE standard for Information Technology, "IEEE Std. 802.15.4, Part. 15.4: Wireless Medium Access Control (MAC)

and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks", n.d., <http://standards.ieee.org/findstds/standard/802.15.4-2015.html>.

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

[RFC6550] Winter, T., Ed., Thubert, P., Ed., Brandt, A., Hui, J., Kelsey, R., Levis, P., Pister, K., Struik, R., Vasseur, JP., and R. Alexander, "RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks", RFC 6550, DOI 10.17487/RFC6550, March 2012, <https://www.rfc-editor.org/info/rfc6550>.

[RFC7416] Tsao, T., Alexander, R., Dohler, M., Daza, V., Lozano, A., and M. Richardson, Ed., "A Security Threat Analysis for the Routing Protocol for Low-Power and Lossy Networks (RPLs)", RFC 7416, DOI 10.17487/RFC7416, January 2015, <https://www.rfc-editor.org/info/rfc7416>.

[RFC7554] Watteyne, T., Ed., Palattella, M., and L. Grieco, "Using IEEE 802.15.4e Time-Slotted Channel Hopping (TSCH) in the Internet of Things (IoT): Problem Statement", RFC 7554, DOI 10.17487/RFC7554, May 2015, <https://www.rfc-editor.org/info/rfc7554>.

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

[RFC9031] Vuini, M., Ed., Simon, J., Pister, K., and M. Richardson, "Constrained Join Protocol (CoJP) for 6TiSCH", RFC 9031, DOI 10.17487/RFC9031, May 2021, <https://www.rfc-editor.org/info/rfc9031>.

[RFC9032] Dujovne, D., Ed. and M. Richardson, "Encapsulation of 6TiSCH Join and Enrollment Information Elements", RFC 9032, DOI 10.17487/RFC9032, May 2021, <https://www.rfc-editor.org/info/rfc9032>.

8.2. Informative References

[I-D.ietf-roll-capabilities]
Jadhav, R., Thubert, P., Richardson, M., and R. N. Sahoo, "RPL Capabilities", Work in Progress, Internet-Draft,

draft-ietf-roll-capabilities-09, 9 November 2021, <https://datatracker.ietf.org/doc/html/draft-ietf-roll-capabilities-09>.

Appendix A. Change history

version 00.

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Mode of Operation extension
draft-ietf-roll-mopex-07

Abstract

The Routing Protocol for Low-Power and Lossy Networks (RPL) can have different modes of operation (MOP) to allow nodes to agree on the basic primitives that must be supported to join a network. The MOP field defined in RFC6550 is fast depleting. This document specifies an extended MOP option for future use.

Status of This Memo

This Internet-Draft is submitted in full conformance with the provisions of BCP 78 and BCP 79.

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1. Introduction

RPL [RFC6550] specifies a proactive distance-vector based routing scheme. The protocol creates a DAG-like structure that operates with a given "Mode of Operation" (MOP) determining the minimum and mandatory set of primitives to be supported by all the participating nodes.

MOP as per [RFC6550] is a 3-bit value carried in DIO messages and is specific to the RPL Instance. The recipient of the DIO message can join the specified network as a router only when it can support the primitives as required by the mode of operation value. For example, in the case of MOP=3 (Storing MOP with multicast support), the nodes can join the network as routers only when they can handle the DAO advertisements from the peers and manage routing tables. The 3-bit value is fast depleting and requires replenishment. This document introduces a mechanism to extend the mode of operation values.

This document further extends the RPL Control Option syntax to handle generic flags. The primary aim of these flags is to define the behavior of a node not supporting the given control type. If a node does not support a given RPL Control Option, there are following possibilities:

Strip off the option

Copy the option as-is

Ignore the message containing this option

Let the node join in only as a leaf to this parent

1.1. Requirements Language and Terminology

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.

MOP: Mode of Operation. Identifies the mode of operation of the RPL Instance as administratively provisioned at and distributed by the DODAG root.

MOPex: Extended MOP: This document extends the MOP values over a bigger range. This extension of MOP is called MOPex.

DAO: Destination Advertisement Object (see Section 6.4 of [RFC6550])

DIO: DODAG Information Object (see Section 6.3 of [RFC6550])

This document uses the terminology described in [RFC6550]. For the sake of readability, some of the known relevant terms are repeated in this section.

2. Requirements for this document

The following are the requirements considered for this document:

REQ1: MOP extension. The 3-bits MOP as defined in [RFC6550] is fast depleting. A MOP extension needs to extend the possibility of adding new MOPs in the future.

REQ2: Backwards compatibility. The new options and new fields in the DIO message should be backward compatible i.e. if there are nodes that support old MOPs they could still operate in their RPL Instances.

3. Extended MOP Control Message Option

This document assigns MOP value 7 to be used as an extender Section 7. A DIO message with a MOP value of 7 indicates that the MOP for RPL instance is contained in the Extended MOP (MOPex) option.

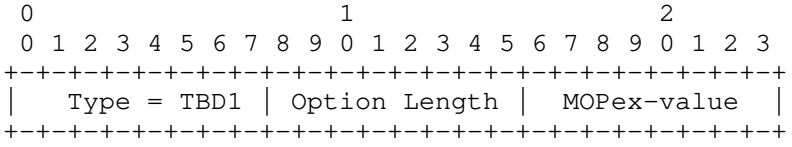

Figure 1: Extended MOP Option

The Option Length value MUST be less than or equal to 2. An Option Length value of zero is invalid and the implementation MUST silently ignore the DIO on receiving a value of zero. Section 6.7.1 of [RFC6550] explains how to interpret Option Length and subsequent Option Data (which is MOPex-value in this context).

3.1. Handling MOPex

The MOPex option MUST be used only if the DIO MOP is 7. If the DIO MOP is 7 and if the MOPex option is not present or invalid then the DIO MUST be silently ignored. If the DIO MOP is less than 7 then MOPex MUST NOT be used. In case the base MOP is 7 and if the MOPex option is present, then the implementation MUST use the MOPex value.

Note that [RFC6550] allows a node that does not support the received MOP to still join the network as a leaf node. This semantics continues to be true even in the case of MOPex. All the general assumptions that are applicable in the context of MOP are applicable in the context of MOPex as well.

3.2. Use of values 0-6 in the MOPex option

The MOPex option should also be used for existing MOP values 0-6. The use of current MOPs (values 0 to 6) in MOPex indicates that the MOP might be supported with an extended set of semantics e.g., the capability options [I-D.ietf-roll-capabilities].

4. Extending RPL Control Options

Section 6.7.1 of [RFC6550] describes the RPL Control Message Option Generic Format. This document extends the format as follows:

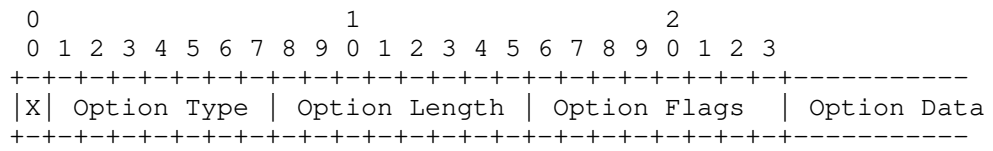

Figure 2: Extended RPL Option Format

The new fields in the Extended RPL Option are specified as follows:

Option Type: 8-bit identifier of the type of option. The Option Type values are assigned by IANA (see Section 20.4 of [RFC6550]).

'X' bit in Option Type: Value 1 indicates that this is an extended option. If the 'X' flag is set, a 1-byte Option Flags field follows the Option Length field.

Option Length: 8-bit unsigned integer, representing the length in octets of the option, not including the Option Type and Length fields. Option Flags and variable length Option Data fields are included in the length.

Option Flags: 8-bit unsigned integer, representing flags in the context of the Extended RPL Control Option. This document defines three flags 'J', 'C', and 'I'. These flags only apply if the Option Type is unknown or unsupported.

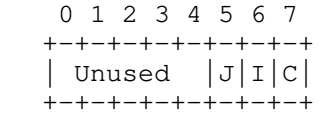

Figure 3: Option Flags in Extended RPL Control Option

'J' (Join) flag: If set, the node MAY only join the network as a leaf.

'C' (Copy) flag: If set, the node MUST copy this Option Type in the DIO message it generates. If unset, the node MUST strip off the Option and process the message.

'I' (Ignore) flag: If set, the node MUST ignore the whole message regardless of the setting of the J and C flags.

Note that this format does not deprecate the previous format, it simply extends it. The new format is applicable only when the most significant bit (MSB), 'X' flag, of the Option Type is set. Option Type 0x80 to 0xFF are thus applicable only as extended options.

'J' bit	'C' bit	Handling
0	0	Strip off the option, and the node can join as RPL router
0	1	Copy the option, and the node can join as RPL router
1	NA	Join as leaf

Table 1: Option Flags handling

5. Implementation Considerations

In [RFC6550], it was possible to discard an unsupported MOP just by inspecting the DIO base object. With the extensions in this document, the MOPex is in a control message option and thus discarding of the DIO message can only happen after inspecting the message options.

An implementation should carefully set the Option Flags considering implications of nodes not supporting the corresponding Option Type.

Unsetting the 'J' flag means that a node receiving an unsupported Option Type would be allowed to join as a RPL router. Thus the implementation should carefully consider the implications of such a node joining the network as a RPL router.

Setting the 'C' (Copy) bit should be carefully considered since the node would copy the Option of its preferred parent whose DIO it has accepted from the set of parent nodes.

6. Acknowledgements

Thank you Dominique Barthel for important review/feedback on extending Control Options. Thanks to Alvaro Retana for shaping the final version with detailed review comments.

7. IANA Considerations

7.1. Mode of operation: MOPex

IANA is requested to assign a new Mode of Operation, named "MOPex" for MOP extension under the RPL registry. The value of 7 is to be assigned from the "Mode of Operation" space [RFC6550].

Value	Description	Reference
7	MOPex	This document

Table 2: Mode of Operation

This document updated [RFC9008] to remove the reservation on Mode of Operation value 7. IANA is requested to assign the Mode of Operation value 7 to MOPex, as shown in Table 2. As shown there, all other references related to value 7 are to be removed. IANA is also requested to replace the reference to [RFC9008] in the overall registry with a reference to this document.

7.2. New option: Extended MOP (MOPex)

IANA is requested to assign a value from the RPL Control Message Options registry for the Extended MOP (MOPex) option Section 3 as shown in Table 3.

Value	Meaning	Reference
TBD1	Extended MOP (MOPex)	This document

Table 3: New options

7.3. New Registry for MOPex value

IANA is requested to create a registry for the MOPex-value Section 3. This registry should be located in the Routing Protocol for Low Power and Lossy Networks (RPL) group. New MOPex values may be allocated only by an IETF review. Each value is tracked with the following qualities:

* MOPex value

* Description

* Reference

MOPex Value	Description	Reference
0 to 6	MOP	[RFC6550]

Table 4: Registry for MOPex values

7.4. Change in RPL Control Option field

IANA is requested to modify the RPL Control Message Options registry to include an Extended Control Options range as shown in Table 5. IANA is also requested to add [this document] as a reference for this updated registry.

Range	Option Type	Reference
0x00 to 0x7f	Base Options	[RFC6550]
0x80 to 0xFf	Extended Options	[this document]

Table 5: Registry for RPL Control Option

8. Security Considerations

The options defined in this document are carried in the base message objects as defined in [RFC6550]. The RPL control message options are protected by the same security mechanisms that protect the base messages. As such, the Security Consideration in [RFC6550] apply.

The use of MOP 7 can reveal that the node has been upgraded or is running a old feature set. This document assumes that the base messages that carry these options are protected by RPL security mechanisms and thus are not visible to a malicious node.

9. References

9.1. Normative References

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

[RFC6550] Winter, T., Ed., Thubert, P., Ed., Brandt, A., Hui, J., Kelsey, R., Levis, P., Pister, K., Struik, R., Vasseur, JP., and R. Alexander, "RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks", RFC 6550, DOI 10.17487/RFC6550, March 2012, <https://www.rfc-editor.org/info/rfc6550>.

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

[RFC9008] Robles, M.I., Richardson, M., and P. Thubert, "Using RPI Option Type, Routing Header for Source Routes, and IPv6-in-IPv6 Encapsulation in the RPL Data Plane", RFC 9008, DOI 10.17487/RFC9008, April 2021, <https://www.rfc-editor.org/info/rfc9008>.

9.2. Informative References

[I-D.ietf-roll-capabilities]
Jadhav, R., Thubert, P., Richardson, M., and R. N. Sahoo, "RPL Capabilities", Work in Progress, Internet-Draft, draft-ietf-roll-capabilities-09, 9 November 2021, <https://datatracker.ietf.org/doc/html/draft-ietf-roll-capabilities-09>.

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Common Ancestor Objective Function and Parent Set DAG Metric Container Extension
draft-ietf-roll-nsa-extension-12

Abstract

High reliability and low jitter can be achieved by being able to send data packets through multiple paths, via different parents, in a network. This document details how to exchange the necessary information within RPL control packets to let a node better select the different parents that will be used to forward a packet over different paths. This document also describes the Objective Function which takes advantage of this information to implement multi-path routing.

Status of This Memo

This Internet-Draft is submitted in full conformance with the provisions of BCP 78 and BCP 79.

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This Internet-Draft will expire on 11 May 2024.

Table of Contents

1. Introduction

Networks in the industrial context must provide stringent guarantees in terms of reliability and predictability, with this domain being one of the main ones addressed by Deterministic Networking [RFC8557]. One of the ways of achieving such guarantees is through Packet Replication and Elimination (PRE) (Section 4.5.3 of [RFC9030]), a technique which allows redundant paths in the network to be utilized for traffic requiring higher reliability. Another is to have pre-selected backup paths on standby for quick packet retransmission when packet failures occur. Load-balancing can be also used to make sure that not all traffic passes through the same nodes, to more evenly spread the packet forwarding load. Allowing industrial applications to function over wireless networks requires the application of the principles and architecture of Deterministic Networking [RFC8655]. This results in designs that aim at optimizing packet delivery rate

and bounding latency. Additionally, nodes operating on battery need to minimize their energy consumption.

As an example, to meet this goal, IEEE Std. 802.15.4 [IEEE802154] provides Time-Slotted Channel Hopping (TSCH), a mode of operation that uses a common communication schedule based on timeslots to allow deterministic medium access as well as channel hopping to work around radio interference. However, since TSCH uses retransmissions in the event of a failed transmission, end-to-end latency and jitter performance can deteriorate.

Furthermore, the 6TiSCH working group, focusing on IPv6 over IEEE Std. 802.15.4-TSCH, has worked on these issues and produced the "6TiSCH Architecture" [RFC9030] to address that case.

Building a multi-path DODAG can be achieved based on the RPL capability of having multiple parents for each node in a network, a subset of which is used to forward packets. In order to select parents to be part of this subset, the RPL Objective Function (OF) needs additional information. This document describes an OF which implements multi-path routing and specifies the transmission of this specific path information.

This document describes a new Objective Function (OF) called the Common Ancestor (CA) OF (see Section 4). A detailed description is given of how the path information is used within the CA OF and how the subset of parents for forwarding packets is selected. This specification defines a new Objective Code Point (OCP) for the CA OF.

For the path information, this specification focuses on the extensions to the DAG Metric Container [RFC6551] required for supplying to the CA OF a part of the information it needs to operate. This information is the RPL [RFC6550] parent address set of a node and it must be sent to potential children of the node. The RPL DIO Control Message is the canonical way of broadcasting this kind of information and therefore its DAG Metric Container [RFC6551] field is used to append a Node State and Attribute (NSA) object. The node's parent address set is stored as an optional TLV within the NSA object. This specification defines the type value and structure for the parent address set TLV (see Section 5).

2. Terminology

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.

The draft uses the following Terminology from other RFCs:

Parent Set (PS): Defined in RPL [RFC6550].

Packet Replication and Elimination (PRE): A method that consists of transmitting multiple copies of a packet using multi-path forwarding over a multi-hop network and that consolidates multiple received packet copies to control flooding. See "Complex Track with Replication and Elimination" in Section 4.5.3 of [RFC9030] for more details.

The draft introduces the following Terminology:

Alternative Parent (AP): An RPL parent in the parent set of a node is used to forward a packet copy when replicating packets.

Alternative Parent (AP) Selection: The mechanism for choosing the next hop node to forward a packet copy when replicating packets.

Preferred Grand Parent (PGP): The preferred parent of the preferred parent of a node.

3. Common Ancestor AP Selection Policies

In the RPL protocol, each node maintains a list of potential parents. When more than one parent is required, as when performing PRE, the RPL DODAG Preferred Parent node is used, as per RPL [RFC6550] parent selection, effectively depending on the OF used. If the CA OF is used, the way this choice is made is described in Section 4. Furthermore, to construct an alternative path toward the root, in addition to the PP node, each node in the network selects one or more parents, called Alternative Parents (APs), from its Parent Set (PS).

There are multiple possible policies for selecting the AP node. This section details three such possible policies.

All three policies defined perform AP selection based on common ancestors, named Common Ancestor Strict, Common Ancestor Medium, and Common Ancestor Relaxed, depending on how restrictive the selection process is. A more restrictive policy will limit flooding but might fail to select an appropriate AP, while a less restrictive one will more often find an appropriate AP but might increase flooding.

All three policies apply their corresponding common ancestor criterion to filter the list of candidate neighbors in the Alternative Parent set.

If after the filtering there are multiple condition-meeting candidate nodes, the node MUST select at least one of them as its AP node. The way this choice is made depends on which OF is used. If the CA OF is used, the way this choice is made is described in Section 4.

3.1. Common Ancestor Strict

In the CA Strict OF the node will check if its Preferred Grand Parent (PGP), the PP of its PP, is the same as the PP of the potential AP.

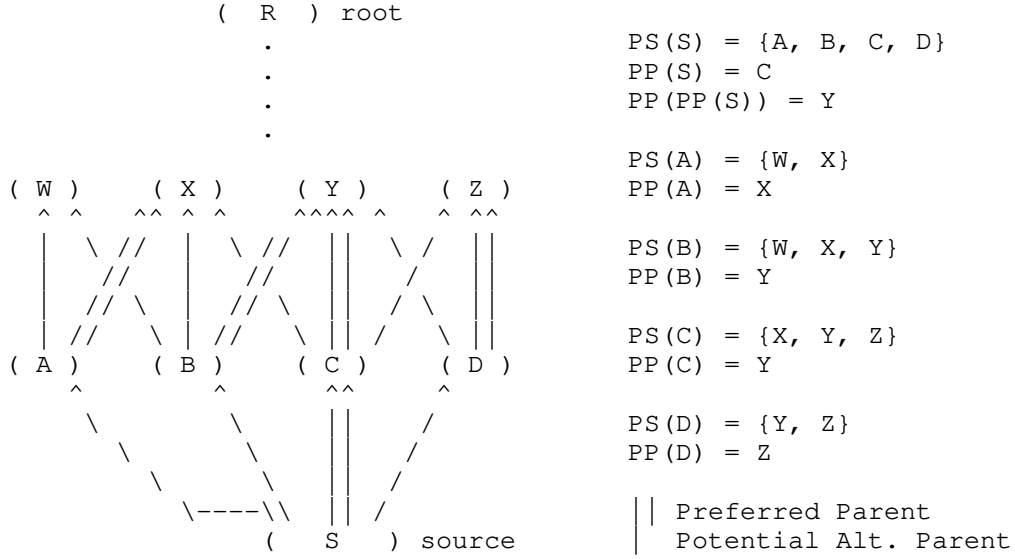

Figure 1: Example Common Ancestor Strict Alternative Parent Selection policy

For example, in Figure 1, the source node S must know its grandparent sets through nodes A, B, C, and D. The Parent Sets (PS) and the Preferred Parents (PS) of nodes A, B, C, and D are shown on the side of the figure. The CA Strict parent selection policy will select an AP for node S for which PP(PP(S)) = PP(AP). Given that PP(PP(S)) = Y:

* Node A: PP(A) = X and therefore it is different than PP(PP(S))

* Node B: PS(B) = Y and therefore it is equal to PP(PP(S))

* Node D: PS(D) = Z and therefore it is different than PP(PP(S))

Therefore, node S MUST select node B as its AP node, since PP(PP(S)) = Y = PP(B).

3.2. Common Ancestor Medium

In the CA Medium OF the node will check if its Preferred Grand Parent (PGP), the PP of its PP, is contained in the PS of the potential AP.

Using the same example, in Figure 1, the CA Medium parent selection policy will select an AP for node S for which PP(PP(S)) is in PS(AP). Given that PP(PP(S)) = Y:

* Node A: PS(A) = {W, X} and therefore PP(PP(S)) is not in the set
* Node B: PS(B) = {W, X, Y} and therefore PP(PP(S)) is in the set
* Node D: PS(D) = {Y, Z} and therefore PP(PP(S)) is in the set

Therefore, S MUST select at least one node among B and D as its AP node.

3.3. Common Ancestor Relaxed

In the CA Relaxed OF the node will check if the Parent Set (PS) of its Preferred Parent (PP) has a node in common with the PS of the potential AP.

Using the same example, in Figure 1, the CA Relaxed parent selection policy will select an AP for node S for which PS(PP(S)) has at least one node in common with PS(AP). Given that PS(PP(S)) = {X, Y, Z}:

* Node A: PS(A) = {W, X} and the common nodes are {X}
* Node B: PS(B) = {W, X, Y} and the common nodes are {X, Y}
* Node D: PS(D) = {Y, Z} and the common nodes are {Y, Z}

Therefore, S MUST select at least one node among A, B, and D as its AP node.

4. Common Ancestor Objective Function

An OF which allows the multiple paths to remain correlated is detailed here. More specifically, when using this OF a node will select an AP node "close" to its PP node to allow the operation of overhearing between parents. Closeness here is not strictly defined, however, the premise is that those candidate parent nodes that have common parents themselves have a higher probability of being within each other’s radio range, though it’s of course not guaranteed. For more details about overhearing and its use in this context see the "Complex Track with Replication and Elimination" in Section 4.5.3 of

[RFC9030]. If multiple potential APs match this condition, one of the APs with the lowest rank will be registered, with the choice between multiple nodes with the same lowest rank being implementation-specific.

The OF described here is an extension of The Minimum Rank with Hysteresis Objective Function (MRHOF) [RFC6719]. The CA OF does not update [RFC6719]. Rather, it uses the existing definition of MRHOF in [RFC6719] to build a new OF (with a new Objective Code Point (OCP)) which provides additional functionality, while maintaining compatibility by retaining the existing functionality of MRHOF for the preferred parent. To be precise, this OF extends MRHOF by specifying how an AP is selected while the selection and switching of the PP remain unaltered. Importantly, the calculation of the rank of the node through each candidate neighbor and the selection of the PP is kept the same as in MRHOF.

How the CA OF differs from MRHOF in a section-by-section manner follows in detail:

[RFC6719], Section 2: "Terminology". Term "Selected Metric":
The CA OF uses only one metric, like MRHOF, for rank calculation, with the same MRHOF semantics. For selecting the AP, the PS TLV (stored in the DIO Metric Container Node State and Attribute (NSA) object body, see Section 5) is used. This additional NSA metric is disregarded for rank calculation.

[RFC6719], Section 3 "The Minimum Rank with Hysteresis Objective Function":
Same as MRHOF extended to AP selection. Minimum Rank path selection and switching apply correspondingly to the AP with the extra CA requirement of having some match between ancestors, according to one of the Common Ancestor AP selection policies defined in Section 3.

[RFC6719], Section 3.1 "Computing the Path Cost":
Same as MRHOF extended to AP selection. If a candidate neighbor does not fulfill the CA requirement then the path cost through that neighbor MUST be set to MAX_PATH_COST, the same value used by MRHOF. As a result, the node MUST NOT select the candidate neighbor as its AP.

[RFC6719], Section 3.2 "Parent Selection":
Same as MRHOF extended to AP selection. To allow hysteresis, AP selection maintains a variable, cur_ap_min_path_cost, which is the path cost of the current AP.

[RFC6719], Section 3.2.1 "When Parent Selection Runs":
Same as MRHOF.

[RFC6719], Section 3.2.2 "Parent Selection Algorithm":
Same as MRHOF extended to AP selection. If the smallest path cost for paths through the candidate neighbors is smaller than cur_ap_min_path_cost by less than PARENT_SWITCH_THRESHOLD (the same variable as MRHOF uses), the node MAY continue to use the current AP. Additionally, if there is no PP selected, there MUST NOT be any AP selected either. Finally, as with MRHOF, a node MAY include up to PARENT_SET_SIZE-1 additional candidate neighbors in its Alternative Parent set. The value of PARENT_SET_SIZE is the same as in MRHOF.

[RFC6719], Section 3.3 "Computing Rank":
Same as MRHOF.

[RFC6719], Section 3.4 "Advertising the Path Cost":
Same as MRHOF.

[RFC6719], Section 3.5 "Working without Metric Containers":
The CA OF can work without metric containers identically to MRHOF. Nodes that transmit DIO messages without the Metric Container will never be selected as an AP by the CA OF of another node but can be selected as the PP as per the operation of MRHOF. Effectively, the lack of Metric Containers is equivalent to operating with a Parent Set TLV where there are no PS IPv6 addresses and the PS Length is 0.

[RFC6719], Section 4 "Using MRHOF for Metric Maximization":
Same as MRHOF.

[RFC6719], Section 5 "MRHOF Variables and Parameters":
Same as MRHOF extended to AP selection. The CA OF operates like MRHOF for AP selection by maintaining separate:

AP: Corresponding to the MRHOF PP. Hysteresis is configured for AP with the same PARENT_SWITCH_THRESHOLD parameter as in MRHOF. The AP MUST NOT be the same as the PP.

Alternative parent set: Corresponding to the MRHOF parent set. The size is defined by the same PARENT_SET_SIZE parameter as in MRHOF. The Alternative parent set MUST be a strict subset of the parent set.

cur_ap_min_path_cost: Corresponding to the MRHOF cur_min_path_cost variable. To support the operation of the hysteresis function for AP selection.

[RFC6719], Section 6 "Manageability":
Same as MRHOF.

[RFC6719], Section 6.1 "Device Configuration":
Same as MRHOF.

[RFC6719], Section 6.2 "Device Monitoring":
Same as MRHOF.

4.1. Usage

All the Common Ancestor AP Selection Policies (Section 3) apply their corresponding criterion to filter the list of candidate neighbors in the Alternative Parent set. The AP is then selected from the Alternative Parent set based on Rank and using hysteresis as is done for the PP in MRHOF. It is noteworthy that the OF uses the same Objective Code Point (OCP): (TBD1) for all policies used.

The PS information can be used by any of the described AP selection policies or other ones not described here, depending on requirements. It is optional for all nodes to use the same AP selection policies. Different nodes may use different AP selection policies since the selection policy is local to each node. For example, using different policies can be used to vary the transmission reliability in each hop. Some suggestions are provided in Appendix B.

5. Node State and Attribute (NSA) object type extension

In order to select their AP node, nodes need to be aware of their grandparent node sets. Within RPL [RFC6550], the nodes use the DODAG Information Object (DIO) Control Message to broadcast information about themselves to potential children. However, RPL [RFC6550], does not define how to propagate information related to the parent set, which is what this document addresses.

DIO messages can carry multiple options, out of which the DAG Metric Container option [RFC6551] is the most suitable structurally and semantically to carry the parent set. The DAG Metric Container option itself can carry different nested objects, out of which the Node State and Attribute (NSA) [RFC6551] is appropriate for transferring generic node state data. Within the Node State and Attribute, it is possible to store optional TLVs representing various node characteristics. As per the Node State and Attribute (NSA) [RFC6551] description, no TLV has been defined for use. This document defines one TLV for transmitting a node’s parent set.

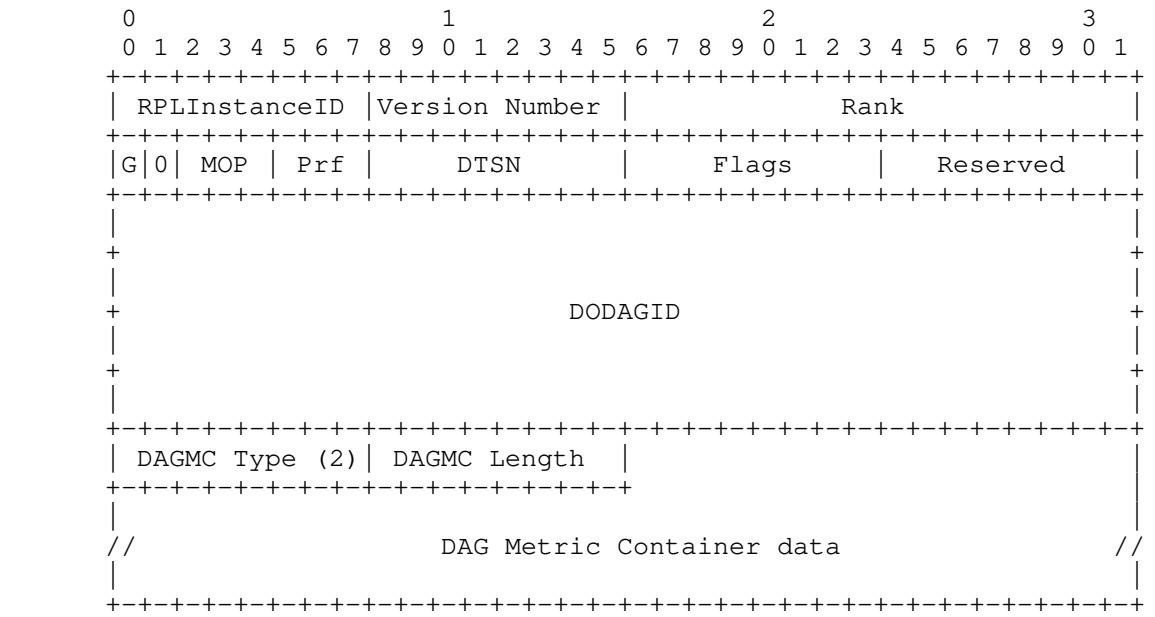

Figure 2: Example DIO Message with a DAG Metric Container option

Figure 2 shows the structure of the DIO Control Message when a DAG Metric Container option is included. The DAG Metric Container option type (DAGMC Type in Figure 2) has the value 0x02 as per the IANA registry for the RPL Control Message Options, and is defined in [RFC6550]. The DAG Metric Container option length (DAGMC Length in Figure 2) expresses the DAG Metric Container length in bytes. DAG Metric Container data holds the actual data and is shown expanded in Figure 3.

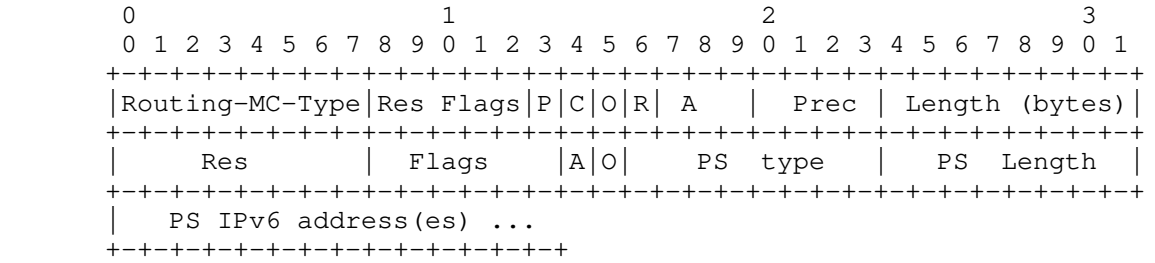

Figure 3: DAG Metric Container (MC) data with Node State and Attribute (NSA) object body and a TLV

The structure of the DAG Metric Container data in the form of a Node State and Attribute (NSA) object with a TLV in the NSA Optional TLVs field is shown in Figure 3. The first 32 bits comprise the DAG Metric Container header and all the following bits are part of the Node State and Attribute object body, as defined in [RFC6551]. This document defines a new TLV, which MUST be carried in the Node State and Attribute (NSA) object Optional TLVs field within the context of the use of the CA OF. The TLV is named Parent Set and is abbreviated as PS in Figure 3.

PS type: The type of the Parent Set TLV. The value is (TBD2).

PS Length: The total length of the TLV value field (PS IPv6 address(es)) in bytes (0 included). The length is an integral multiple of 16, the number of bytes in an IPv6 address.

PS IPv6 address(es) One or more 128-bit IPv6 addresses, without any separator between them. The field consists of one IPv6 address per parent in the parent set. The parent addresses are listed in decreasing order of preference and not all parents in the parent set need to be included. The selection of how many parents from the parent set will be included is left to the implementation. The number of parent addresses in the PS IPv6 address(es) field can be deduced by dividing the length of the PS IPv6 address(es) field in bytes by 16, the number of bytes in an IPv6 address.

5.1. Usage

The PS is used in the process of parent selection, and especially in AP selection since it can help the alternative path to not significantly deviate from the preferred path. The Parent Set is information local to the node that broadcasts it.

The PS is used only within NSA objects configured as a metric, therefore the DAG Metric Container field "C" MUST be 0. Additionally, since the information in the PS needs to be propagated downstream but cannot be aggregated, the DAG Metric Container field "R" MUST be 1. Finally, since the information contained is by definition partial, specifically just the parent set of the DIO-sending node, the DAG Metric Container field "P" MUST be 1.

The presence of incorrectly configured flags MUST render the Parent Set TLV invalid. This case MUST be handled equivalently to operating with a Parent Set TLV where there are no PS IPv6 addresses and the PS Length is 0.

The presence of a PS Length value that is not a multiple of 16 or larger than 240 MUST render the Parent Set TLV invalid. This case MUST be handled equivalently to operating with a Parent Set TLV where there are no PS IPv6 addresses and the PS Length is 0.

6. Controlling PRE

PRE is very helpful when the aim is to increase reliability for a certain path, however, its use creates additional traffic as part of the replication process. It is conceivable that not all paths have stringent reliability requirements. Therefore, a way to control whether PRE is applied to a path's packets SHOULD be implemented. For example, a traffic class label can be used to determine this behavior per flow type as described in Deterministic Networking Architecture [RFC8655].

7. Security Considerations

All the security considerations from [RFC6550], [RFC6551], and [RFC6719] apply.

In this document, the structure of the DIO control message is extended, within the pre-defined DIO options. The additional information is the list of IPv6 addresses of the parent set of the node transmitting the DIO. This use of this additional information can have the following additional potential consequences:

* A malicious node that can send DIOs can use the parent set extension to convince neighbors to route through itself, instead of the normal preferred parent they would use. However, this is already possible with other OFs (like OF0 [RFC6552] and MRHOF [RFC6719]) by reporting a fake rank value in the DIO, thus masquerading as the DODAG root.

8. IANA Considerations

This document requests the allocation of a new value (TBD1) from the "Objective Code Point (OCP)" registry in the "Routing Protocol for Low Power and Lossy Networks (RPL)" registry group. The Description field should have the value "Common Ancestor Objective Function (CAOF)".

This document also requests the allocation of a new value (TBD2) for the "Parent Set" TLV from the "Routing Metric/Constraint TLVs" registry in the "Routing Protocol for Low Power and Lossy Networks (RPL) Routing Metric/Constraint" registry group. The Description field should have the value "Parent Set".

9. Acknowledgments

We are very grateful to Dominique Barthel, Rahul Jadhav, Fabrice Theoleyre, Diego Dujovne, Derek Jianqiang Hou, Michael Richardson, and Alvaro Retana for their comments, feedback, and support which lead to many improvements to this document. We would also like to thank Tomas Lagos Jenschke very much for helping in the implementation and evaluation of this document.

10. References

10.1. Normative references

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

[RFC6550] Winter, T., Ed., Thubert, P., Ed., Brandt, A., Hui, J., Kelsey, R., Levis, P., Pister, K., Struik, R., Vasseur, JP., and R. Alexander, "RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks", RFC 6550, DOI 10.17487/RFC6550, March 2012, <https://www.rfc-editor.org/info/rfc6550>.

[RFC6551] Vasseur, JP., Ed., Kim, M., Ed., Pister, K., Dejean, N., and D. Barthel, "Routing Metrics Used for Path Calculation in Low-Power and Lossy Networks", RFC 6551, DOI 10.17487/RFC6551, March 2012, <https://www.rfc-editor.org/info/rfc6551>.

[RFC6719] Gnawali, O. and P. Levis, "The Minimum Rank with Hysteresis Objective Function", RFC 6719, DOI 10.17487/RFC6719, September 2012, <https://www.rfc-editor.org/info/rfc6719>.

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

10.2. Informative references

[IEEE802154]
IEEE standard for Information Technology, "IEEE Std. 802.15.4, Part. 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks", December 2015, <http://standards.ieee.org/findstds/standard/802.15.4-2015.html>.

[RFC6552] Thubert, P., Ed., "Objective Function Zero for the Routing Protocol for Low-Power and Lossy Networks (RPL)", RFC 6552, DOI 10.17487/RFC6552, March 2012, <https://www.rfc-editor.org/info/rfc6552>.

[RFC8557] Finn, N. and P. Thubert, "Deterministic Networking Problem Statement", RFC 8557, DOI 10.17487/RFC8557, May 2019, <https://www.rfc-editor.org/info/rfc8557>.

[RFC8655] Finn, N., Thubert, P., Varga, B., and J. Farkas, "Deterministic Networking Architecture", RFC 8655, DOI 10.17487/RFC8655, October 2019, <https://www.rfc-editor.org/info/rfc8655>.

[RFC9030] Thubert, P., Ed., "An Architecture for IPv6 over the Time-Slotted Channel Hopping Mode of IEEE 802.15.4 (6TiSCH)", RFC 9030, DOI 10.17487/RFC9030, May 2021, <https://www.rfc-editor.org/info/rfc9030>.

Appendix A. Implementation Status

A research-stage implementation of the PRE mechanism using the proposed extension as part of a 6TiSCH IOT use case was developed at IMT Atlantique, France by Tomas Lagos Jenschke and Remous-Aris Koutsiamanis. It was implemented on the open-source Contiki OS and tested with the Cooja simulator. The DIO DAGMC NSA extension is implemented with a configurable number of parents from the parent set of a node to be reported.

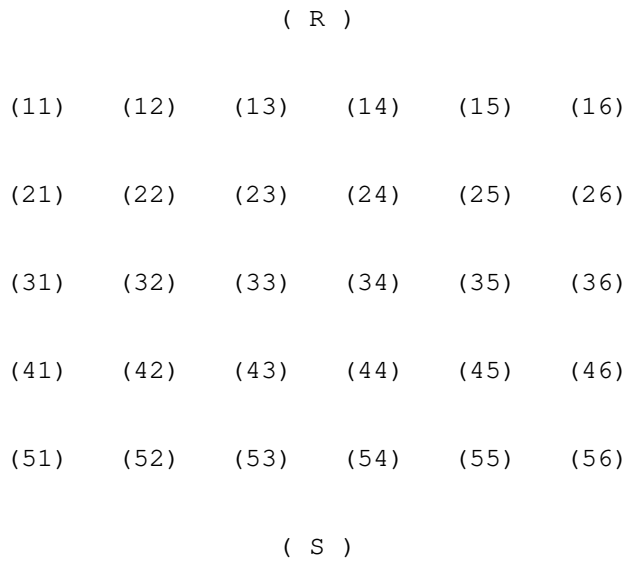

Figure 4: Simulation Topology

The simulation setup is:

Topology: 32 nodes structured in a regular grid as shown in Figure 4. Node S (source) is the only data packet sender and sends data to node R (root). The parent set of each node (except R) is all the nodes in the immediately higher row, the immediately above 6 nodes. For example, each node in {51, 52, 53, 54, 55, 56} is connected to all of {41, 42, 43, 44, 45, 46}. Nodes 11, 12, 13, 14, 15, and 16 have a single upwards link to R.

MAC: TSCH with 1 retransmission

Platform: Cooja

Schedule: Static, 2 timeslots per link from each node to each parent in its parent set, 1 broadcast EB slot, 1 sender-based shared timeslot (for DIO and DIS) per node (total of 32).

Simulation lifecycle: Allow link formation for 100 seconds before starting to send data packets. Afterward, S sends data packets to R. The simulation terminates when 1000 packets have been sent by S.

Radio Links: Every 60 s, a new Packet Delivery Rate is randomly drawn for each link, with a uniform distribution spanning the 70% to 100% interval.

Traffic Pattern: CBR, S sends one non-fragmented UDP packet every 5 seconds to R.

PS extension size: 3 parents.

Routing Methods:

* RPL: The default RPL non-PRE implementation in Contiki OS.

* 2nd ETX: PRE with a parent selection method which picks as AP the 2nd best parent in the parent set based on ETX.

* CA Strict: As described in Section 3.1.

* CA Medium: As described in Section 3.2.

Simulation results:

Routing Method	Average Packet Delivery Rate (%)	Average Traversed Nodes/packet (#)	Average Duplications/ packet (#)
RPL	82.70	5.56	7.02
2nd ETX	99.38	14.43	31.29
CA Strict	97.32	9.86	18.23
CA Medium	99.66	13.75	28.86

Table 1

Links:

* Contiki OS DIO DAGMC NSA extension (draft-koutsiamanis-roll-nsa-extension branch) (https://github.com/ariskou/contiki/tree/draft-koutsiamanis-roll-nsa-extension)

* Wireshark dissectors (for the optional PS TLV) - currently merged / in master (https://code.wireshark.org/review/gitweb?p=wireshark.git;a=commit;h=e2f6ba229f45d8ccae2a6405e0ef41f1e61da138)

Appendix B. Choosing an AP selection policy

The manner of choosing an AP selection policy is left to the implementation, for maximum flexibility.

For example, a different policy can be used per traffic type. The network configurator can choose the CA Relaxed policy to increase reliability (thus producing some flooding) for specific, extremely important, alert packets. On the other hand, all normal data traffic uses the CA Strict policy. Therefore, an exception is made just for the alert packets.

Another option would be to devise a new disjoint policy, where the paths are on purpose non-correlated, to increase path diversity and resilience against whole groups of nodes failing. The disadvantage may be increased jitter.

Finally, a network configurator may provide the CA policies with a preference order of Strict > Medium > Relaxed as a means of falling back to more flood-prone policies to maintain reliability.

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18 September 2023

RNFD: Fast border router crash detection in RPL
draft-ietf-roll-rnfd-02

Abstract

By and large, a correct operation of a RPL network requires border routers to be up. In many applications, it is beneficial for the nodes to detect a crash of a border router as soon as possible to trigger fallback actions. This document describes RNFD, an extension to RPL that expedites border router failure detection, even by an order of magnitude, by having nodes collaboratively monitor the status of a given border router. The extension introduces an additional state at each node, a new type of RPL Control Message Options for synchronizing this state among different nodes, and the coordination algorithm itself.

Table of Contents

1. Introduction

RPL is an IPv6 routing protocol for low-power and lossy networks (LLNs) [RFC6550]. Such networks are usually constrained in device energy and channel capacity. They are formed largely of nodes that offer little processing power and memory, and links that are of variable qualities and support low data rates. Therefore, the main challenge that a routing protocol for LLNs has to address is minimizing resource consumption without sacrificing reaction time to network changes.

One of the main design principles adopted in RPL to minimize node resource consumption is delegating much of the responsibility for routing to LLN border routers (LBRs). A network is organized into destination-oriented directed acyclic graphs (DODAGs), each corresponding to an LBR and having all its paths terminate at the LBR. To this end, every node is dynamically assigned a rank representing its distance, measured in some metric, to a given LBR, with the LBR having the minimal rank, which reflects its role as the DODAG root. The ranks allow each non-LBR node to select from among its neighbors (i.e., nodes to which the node has links) those ones that are closer to the LBR than the node itself: the nodes parents in the graph. The resulting DODAG paths, consisting of the node-parent links, are utilized for routing packets upward: to the LBR and outside the LLN. They are also used by nodes to periodically report their connectivity upward to the LBR, which allows in turn for directing packets downward, from the LBR to these nodes, for instance, by means of source routing [RFC6554]. All in all, not only do LBRs participate in routing but also drive the process of DODAG construction and maintenance underlying the protocol.

To play this central role, LBRs are expected to be more capable than regular LLN nodes. They are assumed not to be constrained in computing power, memory, and energy, which often entails a more involved hardware-software architecture and tethered power supply. This, however, also makes them more prone to failures, especially since in large deployments it is often difficult to ensure a backup power supply for every LBR.

1.1. Effects of LBR Crashes

When an LBR crashes, the nodes in its DODAG lose the ability to communicate with other Internet hosts. In addition, a significant fraction of DODAG paths interconnecting the nodes become invalid, as they pass through the LBR. The others also degenerate as a result of DODAG repair attempts, which are bound to fail. In effect, routing inside the DODAG also becomes largely impossible. Consequently, it is desirable that an LBR crash be detected by the nodes fast, so that they can leave the broken DODAG and join another one or trigger additional application- or deployment-dependent fallback mechanisms, thereby minimizing the negative impact of the disconnection.

Since all DODAG paths lead to the corresponding LBR, detecting its crash by a node entails dropping all parents and adopting an infinite rank, which reflects the nodes inability to reach the LBR. Depending on the deployment settings, the node can then remain in such a state, join a different DODAG, or even become itself the root of a floating DODAG. In any case, however, achieving this state for all nodes is slow, can generate heavy traffic, and is difficult to implement correctly [Iwanicki16] [Paszkowska19] [Ciolkosz19].

To start with, tearing down all DODAG paths requires each of the LBRs neighbors to detect that its link with the LBR is no longer up. Otherwise, any of the neighbors unaware of this fact can keep advertising a finite rank and can thus be other nodes parent or ancestor in the DODAG: such nodes will incorrectly believe they have a valid path to the LBR. Detecting a crash of a link by a node normally happens when the node has observed sufficiently many forwarding failures over the link. Therefore, considering the low-data-rate applications of LLNs, the period from the crash to the moment of eliminating from the DODAG the last link to the LBR may be long. Subsequently learning by all nodes that none of their links can form any path leading to the LBR also adds latency, partly due to parent changes that the nodes independently perform in attempts to repair their broken paths locally. Since a non-LBR node has only local knowledge of the network, potentially inconsistent with that of other nodes, such parent changes often produce paths containing loops, which have to be broken before all nodes can conclude that no path to the LBR exists globally. Even with RPLs dedicated loop detection mechanisms [RFC6553], this also requires traffic, and hence time. Finally, switching a parent or discovering a loop can also generate cascaded bursts of control traffic, owing to the adaptive Trickle algorithm for exchanging DODAG information [RFC6202]. Overall, the behavior of the network when handling an LBR crash is highly suboptimal, thereby not being in line with RPLs goals of minimizing resource consumption and reaction latencies.

1.2. Design Principles

To address this issue, this document proposes an extension to RPL, dubbed Root Node Failure Detector (RNFD). To minimize the time and traffic required to handle an LBR crash, the RNFD algorithm adopts the following design principles, derived directly from the previous observations:

1. Explicitly coordinating LBR monitoring between nodes instead of relying only on the emergent behavior resulting from their independent operation.

2. Avoiding probing all links to the dead LBR so as to reduce the tail latency when eliminating these links from the DODAG.

3. Exploiting concurrency by prompting proactive checking for a possible LBR crash when some nodes suspect such a failure may have taken place, which aims to further reduce the critical path.

4. Minimizing changes to RPLs existing algorithms by operating in parallel and largely independently (in the background), and introducing few additional assumptions.

While these principles do improve RPLs performance under a wide range of LBR crashes, their probabilistic nature precludes hard guarantees for all possible corner cases. In particular, in some scenarios, RNFDs operation may result in false negatives, but these situations are peculiar and will eventually be handled by RPLs own aforementioned mechanisms. Likewise, in some scenarios, notably involving highly unstable links, false positives may occur, but they can be alleviated as well. In any case, the principles also guarantee that RNFD can be deactivated at any time, if needed, in which case RPLs operation is unaffected.

2. Terminology

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.

The Terminology used in this document is consistent with and incorporates that described in Terms Used in Routing for Low-Power and Lossy Networks (LLNs) [RFC7102], RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks [RFC6550], and The Routing Protocol for Low-Power and Lossy Networks (RPL) Option for Carrying RPL Information in Data-Plane Datagrams [RFC6553]. Other terms in use in LLNs can be found in Terminology for Constrained-Node Networks [RFC7228].

In particular, the following acronyms appear in the document:

DIO DODAG Information Object (a RPL message)

DIS DODAG Information Solicitation (a RPL message)

DODAG Destination-Oriented Directed Acyclic Graph

LLN Low-power and Lossy Network

LBR LLN Border Router

In addition, the document introduces the following concepts:

Sentinel One of the two roles that a node can play in RNFD. For a given DODAG Version, a Sentinel node is the DODAG roots neighbor that monitors the DODAG roots status. There are normally multiple Sentinels for a DODAG root. However, being the DODAG roots neighbor need not imply being Sentinel.

Acceptor The other of the two roles that a node can play in RNFD. For a given DODAG Version, an Acceptor node is a node that is not Sentinel.

Locally Observed DODAG Roots State (LORS) A nodes local knowledge of the DODAG roots status, specifying in particular whether the DODAG root is up.

Conflict-Free Replicated Counter (CFRC) Conceptually represents a dynamic set whose cardinality can be estimated. It defines a partial order on its values and supports element addition and union. The union operation is order- and duplicate-insensitive, that is, idempotent, commutative, and associative.

3. Overview

As mentioned previously, LBRs are DODAG roots in RPL, and hence a crash of an LBR is global in that it affects all nodes in the corresponding DODAG. Therefore, each node running RNFD for a given DODAG explicitly tracks the DODAG roots current condition, which is referred to as Locally Observed DODAG Roots State (LORS), and synchronizes its local knowledge with other nodes.

Since monitoring the condition of the DODAG root is performed by tracking the status of its links (i.e., whether they are up or down), it must be done by the roots neighbors; other nodes must accept their observations. Consequently, depending on their roles, non-root nodes are divided in RNFD into two disjoint groups: Sentinels and Acceptors. A Sentinel node is the DODAG roots neighbor that monitors its link with the root. The DODAG root thus normally has multiple Sentinels but being its neighbor need not imply being Sentinel. An Acceptor node is in turn a node that is not Sentinel. Acceptors thus mainly collect and propagate Sentinels observations. More information on Sentinel selection can be found in Section 6.1.

3.1. Protocol State Machine

The possible values of LORS and transitions between them are depicted in Figure 1. States UP and GLOBALLY DOWN can be attained by both Sentinels and Acceptors; states SUSPECTED DOWN and LOCALLY DOWNby Sentinels only.

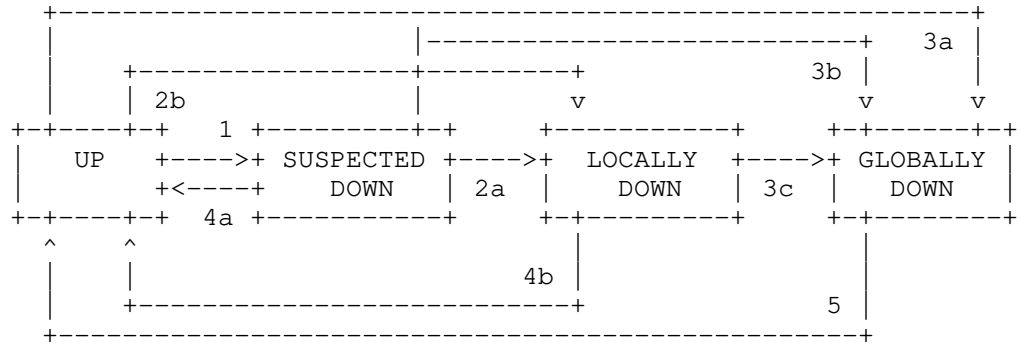


Figure 1: RNFD States and Transitions

To begin with, when any node joins a DODAG Version, the DODAG root must appear alive, so the node initializes RNFD with its LORS equal to UP. For a properly working DODAG root, the node remains in state UP.

However, when a nodeacting as Sentinelstarts suspecting that the root may have crashed, it changes its LORS to SUSPECTED DOWN (transition 1 in Figure 1). The transition from UP to SUSPECTED DOWN can happen based on the nodes observations at either the data plane, for instance, link-layer triggers about missing hop-by-hop acknowledgments for packets forwarded over the nodes link to the root, or the control plane, for example, a significant growth in the number of Sentinels already suspecting the root to be dead. In state SUSPECTED DOWN, the Sentinel node may verify its suspicion and/or inform other nodes about the suspicion. When this has been done, it changes its LORS to LOCALLY DOWN (transition 2a). In some cases, the verification need not be performed and, as an optimization, a direct transition from UP to LOCALLY DOWN (transition 2b) can be done instead.

If sufficiently many Sentinels have their LORS equal to LOCALLY DOWN, all nodesSentinels and Acceptorsconsent globally that the DODAG root must have crashed and set their LORS to GLOBALLY DOWN, irrespective of the previous value (transitions 3a, 3b, and 3c). State GLOBALLY DOWN is terminal in that the only transition any node can perform from this to another state (transition 5) takes

place when the node joins a new DODAG version. When a node is in state GLOBALLY DOWN, RNFD forces RPL to maintain an infinite rank and no parent, thereby preventing routing packets upward in the DODAG. In other words, this state represents a situation in which all non-root nodes agree that the current DODAG version is unusable, and hence, to recover, the root has to give a proof of being alive by initiating a new DODAG Version.

In contrast, if a nodeeither Sentinel or Acceptoris in state UP, RNFD does not influence RPLs packet forwarding: a node can route packets upward if it has a parent. The same is true for a Sentinel node in states SUSPECTED DOWN and LOCALLY DOWN. Finally, while in any of the two states, a Sentinel node may observe some activity of the DODAG root, and hence decide that its suspicion is a mistake. In such a case, it returns to state UP (transitions 4a and 4b).

3.2. Counters and Communication

To enable arriving at a global conclusion that the DODAG root has crashed (i.e., transiting to state GLOBALLY DOWN), all nodes count locally and synchronize among each other the number of Sentinels considering the root to be dead (i.e., those in state LOCALLY DOWN). This process employs structures referred to as conflict-free replicated counters (CFRCs). They are stored and modified independently by each node and are disseminated throughout the network in options added to RPL link-local control messages: DODAG Information Objects (DIOs) and DODAG Information Solicitations (DISs). Upon reception of such an option from its neighbor, a node merges the received counter with its local one, thereby obtaining a new content for its local counter.

The merging operation is idempotent, commutative, and associative. Moreover, all possible counter values are partially ordered. This enables ensuring eventual consistency of the counters acros all nodes, irrespective of the particular sequence of merges, shape of the DODAG, or general network topology.

Each node in RNFD maintains two CFRCs for a DODAG:

* PositiveCFRC, counting Sentinels that have considered or still consider the root node as alive in the current DODAG Version,

* NegativeCFRC, counting Sentinels that have considered or still consider the root node as dead in the current DODAG Version.

PositiveCFRC is always greater than or equal to the NegativeCFRC in terms of the partial order defined for the counters. The difference between the value of PositiveCFRC and the value of NegativeCFRC is thus nonnegative and estimates the number of Sentinels that still consider the DODAG root node as alive.

4. The RNFD Option

RNFD state synchronization between nodes takes place through the RNFD Option. It is a new type of RPL Control Message Options that is carried in link-local RPL control messages, notably DIOs and DISs. Its main task is allowing the receivers to merge their two CFRCs with the senders CFRCs.

4.1. General CFRC Requirements

CFRCs in RNFD MUST support the following operations:

value(c) Returns a nonnegative integer value corresponding to the number of nodes counted by a given CFRC, c.

zero() Returns a CFRC that counts no nodes, that is, has its value equal to 0.

self() Returns a CFRC that counts only the node executing the operation.

infinity() Returns a CFRC that counts all possible nodes and represents a special value, infinity.

merge(c1, c2) Returns a CFRC that is a union of c1 and c2 (i.e., counts all nodes that are counted by either c1, c2, or both c1 and c2).

compare(c1, c2) Returns the result of comparing c1 to c2.

saturated(c) Returns TRUE if a given CFRC, c, is saturated (i.e., no more new nodes should be counted by it) or FALSE otherwise.

The partial ordering of CFRCs implies that the result of compare(c1, c2) can be either:

* smaller, if c1 is ordered before c2 (i.e., c2 counts all nodes that c1 counts and at least one node that c1 does not count);

* greater, if c1 is ordered after c2 (i.e., c1 counts all nodes that c2 counts and at least one node that c2 does not count);

* equal, if c1 and c2 are the same (i.e., they count the same nodes);

* incomparable, otherwise.

In particular, zero() is smaller than all other values and infinity() is greater than any other value.

The properties of merging in turn can be formalized as follows for any c1, c2, and c3:

* idempotence: c1 = merge(c1, c1);

* commutativity: merge(c1, c2) = merge(c2, c1);

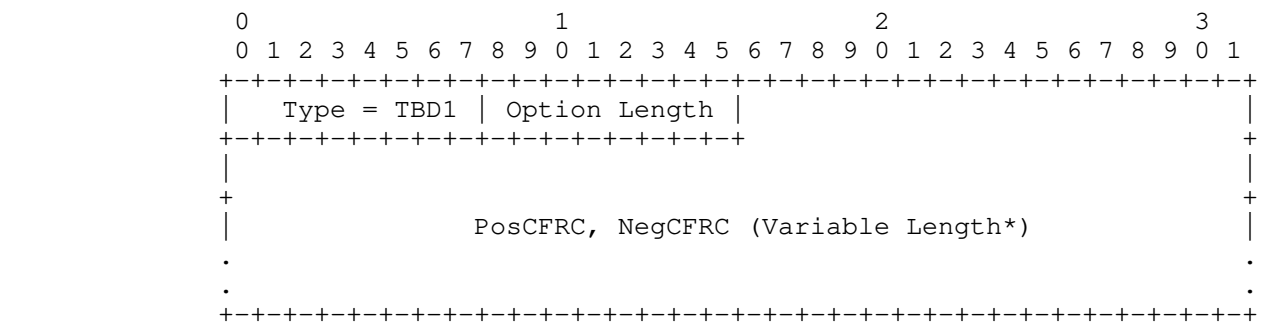
* associativity: merge(c1, merge(c2, c3)) = merge(merge(c1, c2), c3).

In particular, merge(c, zero()) always equals c while merge(c, infinity()) always equals infinity().

There are many algorithmic structures that can provide the aforementioned properties of CFRC. Although in principle RNFD does not rely on any specific one, the option adopts so-called linear counting [Whang90].

4.2. Format of the Option

The format of the RNFD Option conforms to the generic format of RPL Control Message Options:



The '*' denotes that, if present, the fields have equal lengths.

Figure 2: Format of the RNFD Option

Option Type TBD1

Option Length 8-bit unsigned integer. Denotes the length of the option in octets excluding the Option Type and Option Length fields. Its value MUST be even. A value of 0 denotes that RNFD is disabled in the current DODAG Version.

PosCFRC, NegCFRC Two variable-length, octet-aligned bit arrays carrying the senders PositiveCFRC and NegativeCFRC, respectively.

The length of the arrays constituting the PosCFRC and NegCFRC fields is the same and is derived from Option Length as follows. The value of Option Length is divided by 2 to obtain the number of octets each of the two arrays occupies. The resulting number of octets is multiplied by 8 which yields an upper bound on the number of bits in each array. As the actual bit length of each of the arrays, the largest prime number less than the upper bound is assumed. For example, if the value of Option Length is 16, then each array occupies 8 octets, and its actual bit length is 61, as this is the largest prime number less than 64.

Furthermore, for any bit equal to 1 in the NegCFRC, the bit with the same index MUST be equal to 1 also in the PosCFRC. Any unused bits (i.e., the bits beyond the actual bit length of each of the arrays) MUST be equal to 0. Finally, if PosCFRC has all its bits equal to 1, then NegCFRC MUST also have all its bits equal to 1.

The CFRC operations are defined for such bit arrays of a given length as follows:

value(c) Returns the smallest integer value not less than -LT*ln(L0/LT), where ln() is the natural logarithm function, L0 is the number of bits equal to 0 in the array corresponding to c and LT is the bit length of the array.

zero() Returns an array with all bits equal to 0.

self() Returns an array with a single bit, selected uniformly at random, equal to 1.

infinity() Returns an array with all bits equal to 1.

merge(c1, c2) Returns a bit array that constitutes a bitwise OR of c1 and c2, that is, a bit in the resulting array is equal to 0 only if the same bit is equal to 0 in both c1 and c2.

compare(c1, c2) Returns:

* equal if each bit of c1 is equal to the corresponding bit of c2;

* less if c1 and c2 are not equal and, for each bit equal to 1 in c1, the corresponding bit in c2 is also equal to 1;

* greater if c1 and c2 are not equal and, for each bit equal to 1 in c2, the corresponding bit in c1 is also equal to 1;

* incomparable, otherwise.

saturated(c) Returns TRUE, if more than 63% of the bits in c are equal to 1, or FALSE, otherwise.

5. RPL Router Behavior

Although RNFD operates largely independently of RPL, it does need interact with RPL and the overall protocol stack. These interactions are described next and can be realized, for instance, by means of event triggers.

5.1. Joining a DODAG Version and Changing the RNFD Role

Whenever RPL running at a node joins a DODAG Version, RNFDif activeMUST assume for the node the role of Acceptor. Accordingly, it MUST set its LORS to UP and its PositiveCFRC and NegativeCFRC to zero().

The role MAY then change between Acceptor and Sentinel at any time. However, while a switch from Sentinel to Acceptor has no preconditions, for a switch from Acceptor to Sentinel to be possible, _all_ of the following conditions MUST hold:

1. LORS is UP;

2. saturated(PositiveCFRC) is FALSE;

3. a neighbor entry for the DODAG root is present in RPLs DODAG parent set;

4. the neighbor is considered reachable via its link-local IPv6 address.

A role change also REQUIRES appropriate updates to LORS and CFRCs, so that the node is properly accounted for. More specifically, when changing its role from Acceptor to Sentinel, the node MUST add itself to its PositiveCFRC as follows. It MUST generate a new CFRC value, selfc = self(), and MUST replace its PositiveCFRC, denoted oldpc, with newpc = merge(oldpc, selfc). In contrast, the effects of a switch from Sentinel to Acceptor vary depending on the nodes value of LORS before the switch:

* for GLOBALLY DOWN, the node MUST NOT modify its LORS, PositiveCFRC, and NegativeCFRC;

* for LOCALLY DOWN, the node MUST set its LORS to UP but MUST NOT modify its PositiveCFRC and NegativeCFRC;

* for UP and SUSPECTED DOWN, the node MUST set its LORS to UP, MUST NOT modify it PositiveCFRC, but MUST add itself to NegativeCFRC, that is, replace its NegativeCFRC, denoted oldnc, with newnc = merge(oldnc, selfc), where selfc is the counter generated with self() when the node last added itself to its PositiveCFRC.

5.2. Detecting and Verifying Problems with the DODAG Root

Only nodes that are Sentinels take active part in detecting crashes of the DODAG Root; Acceptors just disseminate their observations, reflected in the CFRCs.

The DODAG root monitoring SHOULD be based on both internal inputs, notably the values of CFRCs and LORS, and external inputs, such as triggers from RPL and other protocols. External input monitoring SHOULD be performed preferably in a reactive fashion, also independently of RPL, and at both data plane and control plane. In particular, it is RECOMMENDED that RNFD be directly notified of events relevant to the routing adjacency maintenance mechanisms on which RPL relies, such as Layer 2 triggers [RFC5184] or the Neighbor Unreachability Detection [RFC4861] mechanism. Only events concerning the DODAG root need be monitored to this end. For example, RNFD can conclude that there may be problems with the DODAG root if it observes a lack of multiple consecutive L2 acknowledgments for packets transmitted by the node via the link to the DODAG root. Internally, in turn, it is RECOMMENDED that RNFD take action whenever there is a change to its local CFRCs, so that a node can have a chance to participate in detecting potential problems even when normally it would not exchange packets over the link with the DODAG root during some period. In particular, RNFD SHOULD conclude that there may be problems with the DODAG root, when the fraction value(NegativeCFRC)/value(PositiveCFRC) has grown by at least RNFD_SUSPICION_GROWTH_THRESHOLD since the node last set its LORS to UP.

Whenever having its LORS set to UP RNFD concludesbased on either external or internal inputsthat there may be problems with the link with the DODAG root, it MUST set its LORS to either SUSPECTED DOWN or, as an optimization, to LOCALLY DOWN.

The SUSPECTED DOWN value of LORS is temporary: its aim is to give RNFD an additional opportunity to verify whether the link with the DODAG root is indeed down. Depending on the outcome of such verification, RNFD MUST set its LORS to either UP, if the link has been confirmed not to be down, or LOCALLY DOWN, otherwise. The verification can be performed, for example, by transmitting RPL DIS or ICMPv6 Echo Request messages to the DODAG roots link-local IPv6 address and expecting replies confirming that the root is up and reachable through the link. Care SHOULD be taken not to overload the DODAG root with traffic due to simultaneous probes, for instance, random backoffs can be employed to this end. It is RECOMMENDED that the SUSPECTED DOWN value of LORS is attained and verification takes place if RNFDs conclusion on the state of the DODAG root is based only on indirect observations, for example, the aforementioned growth of the CFRC values. In contrast, for direct observations, such as missing L2 acknowledgments, the verification MAY be skipped, with the nodes LORS effectively changing from UP directly to LOCALLY DOWN.

For consistency with RPL, when detecting potential problems with the DODAG root, RNFD also MUST make use of RPLs independent knowledge. More specifically, a node MUST switch its LORS from UP or SUSPECTED DOWN directly to LOCALLY DOWN if a neighbor entry for the DODAG root is removed from RPLs DODAG parent set or the neighbor ceases to be considered reachable via its link-local IPv6 address.

Finally, while having its LORS already equal to LOCALLY DOWN, a node may make an observation confirming that its link with the DODAG root is actually up. In such a case, it SHOULD set its LORS back to UP but MUST NOT do this before the previous conditions 24 necessary for a node to change its role from Acceptor to Sentinel all hold.

To appropriately account for the nodes observations on the state of the DODAG root, the aforementioned LORS transitions are accompanied by changes to the nodes local CFRCs as follows. Changes between UP and SUSPECTED DOWN do not affect any of the two CFRCs. During a switch from UP or SUSPECTED DOWN to LOCALLY DOWN, in turn, the node MUST add itself to its NegativeCFRC, as explained previously. By symmetry, a transition from LOCALLY DOWN to UP REQUIRES the node to add itself to its PositiveCFRC, again, as explained previously.

5.3. Disseminating Observations and Reaching Agreement

Nodes disseminate their observations by exchanging CFRCs in the RNFD Options embedded in link-local RPL control messages, notably DIOs and DISs. When processing such a received option, a nodeacting as Sentinel or AcceptorMUST update its PositiveCFRC and NegativeCFRC to respectively newpc = merge(oldpc, recvpc) and newnc = merge(oldnc, recvnc), where oldpc and oldnc are the values of the nodes PositiveCFRC and NegativeCFRC before the update, while recvpc and recvnc are the received values of option fields PosCFRC and NegCFRC, respectively.

In effect, the nodes value of fraction value(NegativeCFRC)/value(PositiveCFRC) may change. If the fraction reaches at least RNFD_CONSENSUS_THRESHOLD (with value(PositiveCFRC) being greater than zero), then the node consents on the DODAG root being down. Accordingly, it MUST change its LORS to GLOBALLY DOWN and set its PositiveCFRC and NegativeCFRC both to infinity().

The GLOBALLY DOWN value of LORS is terminal: the node MUST NOT change it and MUST NOT modify its CFRCs until it joins a new DODAG Version. With this value of LORS, RNFD at the node MUST also prevent RPL from having any DODAG parent and advertising any Rank other than INFINITE_RANK.

Since the RNFD Option is embedded, among others, in RPL DIO control messages, updates to a nodes CFRCs may affect the sending schedule of these messages, which is driven by the DIO Trickle timer [RFC6206]. It is RECOMMENDED to use for RNFD a dedicated Trickle timer, different from RPLs DIO Trickle timer. In such a setting, whenever RNFDs timer fires and no DIO message containing the RNFD Option has been sent to the link-local all-RPL-nodes multicast IPv6 address since the previous firing, the node sends a DIO message containing the RNFD Option to the address. In contrast, in the absence of a dedicated Trickle timer for RNFD, an implementation SHOULD ensure that the RNFD Option is present in multicast DIO messages sufficiently often to quickly propagate changes to the nodes CFRCs. In either case, a node MUST reset its Trickle timer when it changes its LORS to GLOBALLY DOWN, so that information about the detected crash of the DODAG root is disseminated in the DODAG fast. Likewise, a node SHOULD reset its Trickle timer when any of its local CFRCs changes significantly.

5.4. DODAG Roots Behavior

The DODAG root node MUST assume the role of Acceptor in RNFD and MUST NOT ever switch this role. It MUST also monitor its LORS and local CFRCs, so that it can react to various events.

To start with, the DODAG root MUST generate a new DODAG Version, thereby restarting the protocol, if it changes its LORS to GLOBALLY DOWN, which may happen when the root has restarted after a crash or the nodes have falsely detected its crash. It MAY also generate a new DODAG Version if fraction value(NegativeCFRC)/value(PositiveCFRC) approaches RNFD_CONSENSUS_THRESHOLD, so as to avoid potential interruptions to routing.

Furthermore, the DODAG root SHOULD either generate a new DODAG Version or increase the bit length of its CFRCs if saturated(PositiveCFRC) becomes TRUE. This is a self-regulation mechanism that helps adjust the CFRCs to a potentially large number of Sentinels (see Section 6.1).

In general, issuing a new DODAG Version effectively restarts RNFD. The DODAG root MAY thus perform this operation also in other situations.

5.5. Activating and Deactivating the Protocol on Demand

RNFD can be activated and deactivated on demand, once per DODAG Version. The particular policies for activating and deactivating the protocol are outside the scope of this document. However, the activation and deactivation SHOULD be done at the DODAG root node; other nodes MUST comply.

More specifically, when a non-root node joins a DODAG Version, RNFD at the node is initially inactive. The node MUST NOT activate the protocol unless it receives for this DODAG Version a valid RNFD Option containing some CFRCs, that is, having its Option Length field positive. In particular, if the option accompanies the message that causes the node to join the DODAG Version, the protocol SHOULD be active from the moment of the joining. RNFD then remains active at the node until it is explicitly deactivated or the node joins a new DODAG Version. An explicit deactivation MUST take place when the node receives an RNFD Option for the DODAG Version with no CFRCs, that is, having its Option Length field equal to zero. When explicitly deactivated, RNFD MUST NOT be reactivated unless the node joins a new DODAG Version. In particular, when the first RNFD Option received by the node has its Option Length field equal to zero, the protocol MUST remain deactivated for the entire time the node belongs to the current DODAG Version.

When RNFD at a node is initially inactive for a DODAG Version, the node MUST NOT attach any RNFD Option to the messages it sends (in particular, because it may not know the desired CFRC lengthsee Section 5.6). When the protocol has been explicitly deactivated, the node MAY also decide not to attach the option to its outgoing

messages. However, it is RECOMMENDED that it sends sufficiently many messages with the option to the link-local all-RPL-nodes multicast IPv6 address to allow its neighbors to learn that RNFD has been deactivated in the current DODAG version. In particular, it MAY reset its Trickle timer to this end but also MAY use some reactive mechanisms, for example, replying with a unicast DIO or DIS containing the RNFD Option with no CFRCs to a message from a neighbor that contains the option with some CFRCs, as such a neighbor appears not to have learned about the deactivation of RNFD.

5.6. Processing CFRCs of Incompatible Lengths

The merge() and compare() operations on CFRCs require both arguments to be compatible, that is, to have the same bit length. However, the processing rules for the RNFD Option (see Section 4.2) do not necessitate this. This fact is made use of not only in the mechanisms for activating and deactivating the protocol (see Section 5.5), but also in mechanisms for dynamic adjustments of CFRCs, which aim to enable deployment-specific policies (see Section 6.1). A node thus MUST be prepared to receive the RNFD Option with fields PosCFRC and NegCFRC of a different bit length than the nodes own PositiveCFRC and NegativeCFRC. Assuming that it has RNFD active and that fields PosCFRC and NegCFRC in the option have a positive length, the node MUST react as follows.

If the bit length of fields PosCFRC and NegCFRC is the same as that of the nodes local PositiveCFRC and NegativeCFRC, then the node MUST perform the merges, as detailed previously (see Section 5.3).

If the bit length of fields PosCFRC and NegCFRC is smaller than that of the nodes local PositiveCFRC and NegativeCFRC, then the node MUST ignore the option and MAY reset its Trickle timer.

If the bit length of fields PosCFRC and NegCFRC is greater than that of the nodes local PositiveCFRC and NegativeCFRC, then the node MUST extend the bit length of its local CFRCs to be equal to that in the option and set the CFRCs as follows:

* If the nodes LORS is GLOBALLY DOWN, then both its local CFRCs MUST be set to infinity().

* Otherwise, they both MUST be set to zero(), and the node MUST account for itself in so initialized CFRCs. More specifically, if the node is Sentinel, then it MUST add itself to its PositiveCFRC, as detailed previously. In addition, if its LORS is LOCALLY DOWN, then it MUST also add itself to its NegativeCFRC, again, as explained previously. Finally, the node MUST perform merges of its local CFRCs and the ones received in the option (see Section 5.3) and MAY reset its Trickle timer.

In contrast, if the node is unable to extend its local CFRCs, for example, because it lacks resources, then it MUST stop participating in RNFD, that is, until it joins a new DODAG Version, it MUST NOT send the RNFD Option and MUST ignore this option in received messages.

5.7. Summary of RNFDs Interactions with RPL

In summary, RNFD interacts with RPL in the following manner:

* While having its LORS equal to GLOBALLY DOWN, RNFD prevents RPL from routing packets and advertising upward routes in the corresponding DODAG (see Section 5.3).

* In some scenarios, RNFD triggers RPL to issue a new DODAG Version (see Section 5.4).

* Depending on the implementation, RNFD may cause RPLs DIO Trickle timer resets (see Section 5.3, Section 5.5, and Section 5.6).

* RNFD monitors events relevant to routing adjacency maintenance as well as those affecting RPLs DODAG parent set (see Section 5.1 and Section 5.2).

* Using RNFD entails embedding the RNFD Option into link-local RPL control messages (see Section 4.2).

5.8. Summary of RNFDs Constants

The following is a summary of RNFDs constants:

RNFD_SUSPICION_GROWTH_THRESHOLD A threshold concerning the value of

fraction value(NegativeCFRC)/value(PositiveCFRC). If the value at a Sentinel node grows at least by this threshold since the time the nodes LORS was last set to UP, then the nodes LORS is set to SUSPECTED DOWN or LOCALLY DOWN, which implies that the node suspects or assumes a crash of the DODAG root (see Section 5.2). The default value of the threshold is 0.12. The higher the value the longer the detection period but the lower risk of increased traffic due suspicion verification.

RNFD_CONSENSUS_THRESHOLD A threshold concerning the value of fraction value(NegativeCFRC)/value(PositiveCFRC). If the value at a Sentinel or Acceptor node reaches the threshold, then the nodes LORS is set to GLOBALLY DOWN, which implies that consensus has been reached on the DODAG root node being down (see Section 5.3). The default value of the threshold is 0.51. The higher the value the longer the detection period but the lower the risk of false positives.

The means of configuring the constants at individual nodes are outside the scope of this document.

6. Manageability Considerations

RNFD is largely self-managed, with the exception of protocol activation and deactivation, as well as node role assignment and the related CFRC size adjustment, for which only the aforementioned mechanisms are defined, so as to enable adopting deployment-specific policies. This section outlines some of the possible policies.

6.1. Role Assignment and CFRC Size Adjustment

One approach to node role and CFRC size selection is to manually designate specific nodes as Sentinels in RNFD, assuming that they will have chances to satisfy the necessary conditions for attaining this role (see Section 5.1), and fixing the CFRC bit length to accommodate these nodes.

Another approach is to automate the selection process: in principle, any node satisfying the necessary conditions for becoming Sentinel (see Section 5.1) can attain this role. However, in networks where the DODAG root node has many neighbors, this approach may lead to saturated(PositiveCFRC) quickly becoming TRUE, whichwithout additional measuresmay degrade RNFDs performance. This issue can be handled with a probabilistic solution: if PositiveCFRC becomes saturated with little or no increase in NegativeCFRC, then a new DODAG Version can be issued and a node satisfying the necessary conditions can become Sentinel in this version only with probability 1/2. This process can be continued with the probability being halved

in each new DODAG Version until PositiveCFRC is no longer quickly saturated. Another solution is to increase, potentially multiple times the bit length of the CFRCs by the DODAG root if PositiveCFRC becomes saturated with little or no growth in NegativeCFRC, which does not require issuing a new DODAG Version but lengthens the RNFD Option. In this way, again, a sufficient bit length can be dynamically discovered or the root can conclude that a given bit length is excessive for (some) nodes and resort to the previous solution. Increasing the bit length can be done, for instance, by doubling it, respecting the condition that it has to be a prime number (see Section 4.2).

In either of the solutions, Sentinel nodes SHOULD preferably be stable themselves and have stable links to the DODAG root. Otherwise, they may often exhibit LORS transitions between UP and LOCALLY DOWN or switches between Acceptor and Sentinel roles, which gradually saturates CFRCs. Although as a mitigation the number of such transitions and switches per node MAY be limited, having Sentinels stable SHOULD be preferred.

6.2. Virtual DODAG Roots

RPL allows a DODAG to have a so-called virtual root, that is, a collection of nodes coordinating to act as a single root of the DODAG. The details of the coordination process are left open in the specification [RFC6550] but, from RNFDs perspective, two possible realizations are worth consideration:

* Just a single (primary) node of the nodes comprising the virtual root acts as the actual root of the DODAG. Only when this node fails, does another (backup) node take over. As a result, at any time, at most one of the nodes comprising the virtual root is the actual root.

* More than one of the nodes comprising the virtual root act as actual roots of the DODAG, all advertising the same Rank in the DODAG. When some of the nodes fail, the other nodes may or may not react in any specific way. In other words, at any time, more than one node can be the actual root.

In the first realization, RNFDs operation is largely unaffected. The necessary conditions for a node to become Sentinel (Section 5.1) guarantee that only the current primary root node is monitored by the protocol. This SHOULD be taken into account in the policies for node role assignment, CFRC size selection, and, possibly, the setting of the two thresholds (Section 5.8). Moreover, when a new primary has been elected, to avoid polluting CFRCs with observations on the previous primary, it is RECOMMENDED to issue a new DODAG Version, especially if the new primary has different neighbors compared to the old one.

In the second realization, the fact that the virtual root consists of multiple nodes is transparent to RNFD. Therefore, employing RNFD is such a setting can be beneficial only if the nodes comprising the virtual root may suffer from correlated crashes, for instance, due to global power outages.

7. Security Considerations

RNFD is an extension to RPL and is thus both vulnerable to and benefits from the security issues and solutions described in [RFC6550] and [RFC7416]. Its specification in this document does not introduce new traffic patterns or new messages, for which specific mitigation techniques would be required beyond what can already be adopted for RPL.

In particular, RNFD depends on information exchanged in the RNFD Option. If the contents of this option were compromised, then failure misdetection may occur. One possibility is that the DODAG root may be falsely detected as crashed, which would result in an inability of the nodes to route packets, at least until a new DODAG Version is issued by the root. Another possibility is that a crash of the DODAG root may not be detected by RNFD, in which case RPL would have to rely on its own mechanisms. Moreover, compromising the contents of the RNFD Option may also lead to increased traffic due to DIO Trickle timer resets. Consequently, RNFD deployments are RECOMMENDED to use RPL security mechanisms if there is a risk that control information might be modified or spoofed.

In this context, RNFDs two features are worth highlighting. First, unless all neighbors of a DODAG root are compromised, a false positive can always be detected by the root based on its local CFRCs. If the frequency of such false positives becomes problematic, RNFD can be disabled altogether, for instance, until the problem has been diagnosed. This procedure can be largely automated at LBRs. Second, some types of false negatives can also be detected this way. Those that pass undetected, in turn, are likely not to have major negative consequences on RPL apart from the lack of improvement to its performance upon a DODAG roots crash, at least if RPLs other components are not attacked as well.

8. IANA Considerations

To represent the RNFD Option, IANA is requested to allocate the value TBD1 from the RPL Control Message Options registry (https://www.iana.org/assignments/rpl/rpl.xhtml#control-message-options) of the Routing Protocol for Low Power and Lossy Networks (RPL) registry group.

9. Acknowledgements

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TODO More likely to follow.

10. References

10.1. Normative References

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

[RFC6206] Levis, P., Clausen, T., Hui, J., Gnawali, O., and J. Ko, "The Trickle Algorithm", RFC 6206, DOI 10.17487/RFC6206, March 2011, <https://www.rfc-editor.org/info/rfc6206>.

[RFC6550] Winter, T., Ed., Thubert, P., Ed., Brandt, A., Hui, J., Kelsey, R., Levis, P., Pister, K., Struik, R., Vasseur, JP., and R. Alexander, "RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks", RFC 6550, DOI 10.17487/RFC6550, March 2012, <https://www.rfc-editor.org/info/rfc6550>.

[RFC6553] Hui, J. and JP. Vasseur, "The Routing Protocol for Low-Power and Lossy Networks (RPL) Option for Carrying RPL Information in Data-Plane Datagrams", RFC 6553, DOI 10.17487/RFC6553, March 2012, <https://www.rfc-editor.org/info/rfc6553>.

[RFC6554] Hui, J., Vasseur, JP., Culler, D., and V. Manral, "An IPv6 Routing Header for Source Routes with the Routing Protocol for Low-Power and Lossy Networks (RPL)", RFC 6554, DOI 10.17487/RFC6554, March 2012, <https://www.rfc-editor.org/info/rfc6554>.

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

10.2. Informative References

[Ciolkosz19]
Ciolkosz, P., "Integration of the RNFD Algorithm for Border Router Failure Detection with the RPL Standard for Routing IPv6 Packets", Master's Thesis, University of Warsaw, 2019.

[Iwanicki16]
Iwanicki, K., "RNFD: Routing-layer detection of DODAG (root) node failures in low-power wireless networks", In IPSN 2016: Proceedings of the 15th ACM/IEEE International Conference on Information Processing in Sensor Networks, IEEE, pp. 1--12, DOI 10.1109/IPSN.2016.7460720, 2016, <https://doi.org/10.1109/IPSN.2016.7460720>.

[Paszkowska19]
Paszkowska, A. and K. Iwanicki, "Failure Handling in RPL Implementations: An Experimental Qualitative Study", In Mission-Oriented Sensor Networks and Systems: Art and Science (Habib M. Ammari ed.), Springer International Publishing, pp. 49--95, DOI 10.1007/978-3-319-91146-5_3, 2019, <https://doi.org/10.1007/978-3-319-91146-5_3>.

[RFC4861] Narten, T., Nordmark, E., Simpson, W., and H. Soliman, "Neighbor Discovery for IP version 6 (IPv6)", RFC 4861, DOI 10.17487/RFC4861, September 2007, <https://www.rfc-editor.org/info/rfc4861>.

[RFC5184] Teraoka, F., Gogo, K., Mitsuya, K., Shibui, R., and K. Mitani, "Unified Layer 2 (L2) Abstractions for Layer 3 (L3)-Driven Fast Handover", RFC 5184, DOI 10.17487/RFC5184, May 2008, <https://www.rfc-editor.org/info/rfc5184>.

[RFC6202] Loreto, S., Saint-Andre, P., Salsano, S., and G. Wilkins, "Known Issues and Best Practices for the Use of Long Polling and Streaming in Bidirectional HTTP", RFC 6202, DOI 10.17487/RFC6202, April 2011, <https://www.rfc-editor.org/info/rfc6202>.

[RFC7102] Vasseur, JP., "Terms Used in Routing for Low-Power and Lossy Networks", RFC 7102, DOI 10.17487/RFC7102, January 2014, <https://www.rfc-editor.org/info/rfc7102>.

[RFC7228] Bormann, C., Ersue, M., and A. Keranen, "Terminology for Constrained-Node Networks", RFC 7228, DOI 10.17487/RFC7228, May 2014, <https://www.rfc-editor.org/info/rfc7228>.

[RFC7416] Tsao, T., Alexander, R., Dohler, M., Daza, V., Lozano, A., and M. Richardson, Ed., "A Security Threat Analysis for the Routing Protocol for Low-Power and Lossy Networks (RPLs)", RFC 7416, DOI 10.17487/RFC7416, January 2015, <https://www.rfc-editor.org/info/rfc7416>.

[Whang90] Whang, K.-Y., Vander-Zanden, B.T., and H.M. Taylor, "A Linear-time Probabilistic Counting Algorithm for Database Applications", In ACM Transactions on Database Systems, DOI 10.1145/78922.78925, 1990, <https://doi.org/10.1145/78922.78925>.

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