ROLL
Internet-Draft
Intended status: Standards Track
Expires: September 8, 2019

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March 7, 2019

Asymmetric AODV-P2P-RPL in Low-Power and Lossy Networks (LLNs)
draft-ietf-roll-aodv-rpl-06

Abstract

Route discovery for symmetric and asymmetric Point-to-Point (P2P) traffic flows is a desirable feature in Low power and Lossy Networks (LLNs). For that purpose, this document specifies a reactive P2P route discovery mechanism for both hop-by-hop routing and source routing: Ad Hoc On-demand Distance Vector Routing (AODV) based RPL protocol. Paired Instances are used to construct directional paths, in case some of the links between source and target node are asymmetric.

Status of This Memo

This Internet-Draft will expire on September 8, 2019.

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1. Introduction

RPL[RFC6550] (Routing Protocol for LLNs (Low-Power and Lossy Networks)) is a IPv6 distance vector routing protocol designed to support multiple traffic flows through a root-based Destination-Oriented Directed Acyclic Graph (DODAG). Typically, a router does not have routing information for most other routers. Consequently, for traffic between routers within the DODAG (i.e., Point-to-Point (P2P) traffic) data packets either have to traverse the root in non-storing mode, or traverse a common ancestor in storing mode. Such P2P traffic is thereby likely to traverse longer routes and may suffer severe congestion near the DAG root [RFC6997], [RFC6998].

To discover better paths for P2P traffic flows in RPL, P2P-RPL [RFC6997] specifies a temporary DODAG where the source acts as a temporary root. The source initiates DIOs encapsulating the P2P Route Discovery option (P2P-RDO) with an address vector for both hop-by-hop mode (H=1) and source routing mode (H=0). Subsequently, each intermediate router adds its IP address and multicasts the P2P mode DIOs, until the message reaches the Target Node, which then sends the "Discovery Reply" object. P2P-RPL is efficient for source routing, but much less efficient for hop-by-hop routing due to the extra address vector overhead. However, for symmetric links, when the P2P mode DIO message is being multicast from the source hop-by-hop, receiving nodes can infer a next hop towards the source. When the Target Node subsequently replies to the source along the established forward route, receiving nodes determine the next hop towards the Target Node. For hop-by-hop routes (H=1) over symmetric links, this would allow efficient use of routing tables for P2P-RDO messages instead of the "Address Vector".

RPL and P2P-RPL both specify the use of a single DODAG in networks of symmetric links, where the two directions of a link MUST both satisfy the constraints of the objective function. This disallows the use of asymmetric links which are qualified in one direction. But, application-specific routing requirements as defined in IETF ROLL Working Group [RFC5548], [RFC5673], [RFC5826] and [RFC5867] may be satisfied by routing paths using bidirectional asymmetric links. For this purpose, [I-D.thubert-roll-asymlink] described bidirectional asymmetric links for RPL [RFC6550] with Paired DODAGs, for which the DAG root (DODAGID) is common for two Instances. This can satisfy application-specific routing requirements for bidirectional

asymmetric links in core RPL [RFC6550]. Using P2P-RPL twice with Paired DODAGs, on the other hand, requires two roots: one for the source and another for the target node due to temporary DODAG formation. For networks composed of bidirectional asymmetric links (see Section 5), AODV-RPL specifies P2P route discovery, utilizing RPL with a new MoP. AODV-RPL makes use of two multicast messages to discover possibly asymmetric routes. This provides higher route diversity and can find suitable routes that might otherwise go undetected by RPL. AODV-RPL eliminates the need for address vector overhead in hop-by-hop mode. This significantly reduces the control packet size, which is important for Constrained LLN networks. Both discovered routes (upward and downward) meet the application specific metrics and constraints that are defined in the Objective Function for each Instance [RFC6552]. On the other hand, the point-to-point nature of routes discovered by AODV-RPL can reduce interference near the root nodes and also provide routes with fewer hops, likely improving performance in the network.

The route discovery process in AODV-RPL is modeled on the analogous procedure specified in AODV [RFC3561]. The on-demand nature of AODV route discovery is natural for the needs of peer-to-peer routing in RPL-based LLNs. AODV terminology has been adapted for use with AODV-RPL messages, namely RREQ for Route Request, and RREP for Route Reply. AODV-RPL currently omits some features compared to AODV -- in particular, flagging Route Errors, blacklisting unidirectional links, multihoming, and handling unnumbered interfaces.

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 [RFC2119]. This document uses the following terms:

AODV
: Ad Hoc On-demand Distance Vector Routing[RFC3561].

AODV-RPL Instance
: Either the RREQ-Instance or RREP-Instance

Asymmetric Route
: The route from the OrigNode to the TargNode can traverse different nodes than the route from the TargNode to the OrigNode. An asymmetric route may result from the asymmetry of links, such that only one direction of the series of links fulfills the constraints in route discovery.

Bi-directional Asymmetric Link

A link that can be used in both directions but with different link characteristics.

DIO
DODAG Information Object

DODAG RREQ-Instance (or simply RREQ-Instance)
RPL Instance built using the DIO with RREQ option; used for control message transmission from OrigNode to TargNode, thus enabling data transmission from TargNode to OrigNode.

DODAG RREP-Instance (or simply RREP-Instance)
RPL Instance built using the DIO with RREP option; used for control message transmission from TargNode to OrigNode thus enabling data transmission from OrigNode to TargNode.

Downward Direction
The direction from the OrigNode to the TargNode.

Downward Route
A route in the downward direction.

hop-by-hop routing
Routing when each node stores routing information about the next hop.

on-demand routing
Routing in which a route is established only when needed.

OrigNode
The IPv6 router (Originating Node) initiating the AODV-RPL route discovery to obtain a route to TargNode.

Paired DODAGs
Two DODAGs for a single route discovery process between OrigNode and TargNode.

P2P
Point-to-Point -- in other words, not constrained a priori to traverse a common ancestor.

reactive routing
Same as "on-demand" routing.

RREQ-DIO message
An AODV-RPL MoP DIO message containing the RREQ option. The RPLInstanceID in RREQ-DIO is assigned locally by the OrigNode.

RREP-DIO message
An AODV-RPL MoP DIO message containing the RREP option. The RPLInstanceID in RREP-DIO is typically paired to the one in the associated RREQ-DIO message.

Source routing
A mechanism by which the source supplies the complete route towards the target node along with each data packet [RFC6550].

Symmetric route
The upstream and downstream routes traverse the same routers.

TargNode
The IPv6 router (Target Node) for which OrigNode requires a route and initiates Route Discovery within the LLN network.

Upward Direction
The direction from the TargNode to the OrigNode.

Upward Route
A route in the upward direction.

ART option
AODV-RPL Target option: a target option defined in this document.

3. Overview of AODV-RPL

With AODV-RPL, routes from OrigNode to TargNode within the LLN network are established "on-demand". In other words, the route discovery mechanism in AODV-RPL is invoked reactively when OrigNode has data for delivery to the TargNode but existing routes do not satisfy the application's requirements. The routes discovered by AODV-RPL are not constrained to traverse a common ancestor. Unlike RPL [RFC6550] and P2P-RPL [RFC6997], AODV-RPL can enable asymmetric communication paths in networks with bidirectional asymmetric links. For this purpose, AODV-RPL enables discovery of two routes: namely, one from OrigNode to TargNode, and another from TargNode to OrigNode. When possible, AODV-RPL also enables symmetric route discovery along Paired DODAGs (see Section 5).

In AODV-RPL, routes are discovered by first forming a temporary DAG rooted at the OrigNode. Paired DODAGs (Instances) are constructed according to the AODV-RPL Mode of Operation (MoP) during route formation between the OrigNode and TargNode. The RREQ-Instance is formed by route control messages from OrigNode to TargNode whereas the RREP-Instance is formed by route control messages from TargNode to OrigNode. Intermediate routers join the Paired DODAGs based on the rank as calculated from the DIO message. Henceforth in this

document, the RREQ-DIO message means the AODV-RPL mode DIO message from OrigNode to TargNode, containing the RREQ option (see Section 4.1). Similarly, the RREP-DIO message means the AODV-RPL mode DIO message from TargNode to OrigNode, containing the RREP option (see Section 4.2). The route discovered in the RREQ-Instance is used for transmitting data from TargNode to OrigNode, and the route discovered in RREP-Instance is used for transmitting data from OrigNode to TargNode.

4. AODV-RPL DIO Options

4.1. AODV-RPL DIO RREQ Option

OrigNode sets its IPv6 address in the DODAGID field of the RREQ-DIO message. A RREQ-DIO message MUST carry exactly one RREQ option.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     Type      | Option Length |S|H|X| Compr | L |   MaxRank    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Orig SeqNo   |                                               |
+-+-+-+-+-+-+-+-+                                               |
|                                                               |
|                                                               |
|           Address Vector (Optional, Variable Length)          |
|                                                               |
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 1: DIO RREQ option format for AODV-RPL MoP

OrigNode supplies the following information in the RREQ option:

Type
   The type assigned to the RREQ option (see Section 9.2).

Option Length
   The length of the option in octets, excluding the Type and Length fields. Variable due to the presence of the address vector and the number of octets elided according to the Compr value.

S
   Symmetric bit indicating a symmetric route from the OrigNode to the router transmitting this RREQ-DIO.

H

Set to one for a hop-by-hop route. Set to zero for a source route. This flag controls both the downstream route and upstream route.

X
Reserved.

Compr
4-bit unsigned integer. Number of prefix octets that are elided from the Address Vector. The octets elided are shared with the IPv6 address in the DODAGID. This field is only used in source routing mode (H=0). In hop-by-hop mode (H=1), this field MUST be set to zero and ignored upon reception.

L

2-bit unsigned integer determining the duration that a node is able to belong to the temporary DAG in RREQ-Instance, including the OrigNode and the TargNode. Once the time is reached, a node MUST leave the DAG and stop sending or receiving any more DIOs for the temporary DODAG. The definition for the "L" bit is similar to that found in [RFC6997], except that the values are adjusted to enable arbitrarily long route lifetime.

* 0x00: No time limit imposed.
* 0x01: 16 seconds
* 0x02: 64 seconds
* 0x03: 256 seconds

L is independent from the route lifetime, which is defined in the DODAG configuration option. The route entries in hop-by-hop routing and states of source routing can still be maintained even after the DAG expires.

MaxRank
This field indicates the upper limit on the integer portion of the rank (calculated using the DAGRank() macro defined in [RFC6550]). A value of 0 in this field indicates the limit is infinity.

Orig SeqNo
Sequence Number of OrigNode, defined similarly as in AODV [RFC3561].

Address Vector
A vector of IPv6 addresses representing the route that the RREQ-DIO has passed. It is only present when the 'H' bit is set to 0. The prefix of each address is elided according to the Compr field.

A node MUST NOT join a RREQ instance if its own rank would equal to or higher than MaxRank. Targnode can join the RREQ instance at a rank whose integer portion is equal to the MaxRank. A router MUST discard a received RREQ if the integer part of the advertised rank equals or exceeds the MaxRank limit. This definition of MaxRank is the same as that found in [RFC6997].

4.2. AODV-RPL DIO RREP Option

TargNode sets its IPv6 address in the DODAGID field of the RREP-DIO message. A RREP-DIO message MUST carry exactly one RREP option. TargNode supplies the following information in the RREP option:

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     Type      | Option Length |G|H|X| Compr | L |   MaxRank    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   Shift   |Rsv|                                               |
+-+-+-+-+-+-+-+-+                                               |
|                                                               |
|                                                               |
|           Address Vector (Optional, Variable Length)          |
.                                                               .
.                                                               .
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 2: DIO RREP option format for AODV-RPL MoP

Type
The type assigned to the RREP option (see Section 9.2)

Option Length
The length of the option in octets, excluding the Type and Length fields. Variable due to the presence of the address vector and the number of octets elided according to the Compr value.

G
Gratuitous route (see Section 7).

H
Requests either source routing (H=0) or hop-by-hop (H=1) for the downstream route. It MUST be set to be the same as the 'H' bit in RREQ option.

X
Reserved.

Compr
4-bit unsigned integer. Same definition as in RREQ option.

L
2-bit unsigned integer defined as in RREQ option.

MaxRank
Similarly to MaxRank in the RREQ message, this field indicates the upper limit on the integer portion of the rank. A value of 0 in this field indicates the limit is infinity.

Shift
6-bit unsigned integer. This field is used to recover the original InstanceID (see Section 6.3.3); 0 indicates that the original InstanceID is used.

Rsv
MUST be initialized to zero and ignored upon reception.

Address Vector
Only present when the 'H' bit is set to 0. For an asymmetric route, the Address Vector represents the IPv6 addresses of the route that the RREP-DIO has passed. For a symmetric route, it is the Address Vector when the RREQ-DIO arrives at the TargNode, unchanged during the transmission to the OrigNode.

4.3. **AODV-RPL DIO Target Option**

The AODV-RPL Target (ART) Option is defined based on the Target Option in core RPL [RFC6550]: the Destination Sequence Number of the TargNode is added.

A RREQ-DIO message MUST carry at least one ART Options. A RREP-DIO message MUST carry exactly one ART Option.

OrigNode can include multiple TargNode addresses via multiple AODV-RPL Target Options in the RREQ-DIO, for routes that share the same constraints. This reduces the cost to building only one DODAG. Furthermore, a single Target Option can be used for different TargNode addresses if they share the same prefix; in that case the use of the destination sequence number is not defined in this document.

```
        0                   1                   2                   3
        0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
       +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
       |     Type      | Option Length |  Dest SeqNo   | Prefix Length |
       +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
       |                                                               |
       +                                                               |
       |                Target Prefix (Variable Length)                |
       .                                                               .
       .                                                               .
       +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 3: Target option format for AODV-RPL MoP

Type
   The type assigned to the ART Option

Dest SeqNo

   In RREQ-DIO, if nonzero, it is the last known Sequence Number for TargNode for which a route is desired. In RREP-DIO, it is the destination sequence number associated to the route.

5. Symmetric and Asymmetric Routes

In Figure 4 and Figure 5, BR is the Border Router, O is the OrigNode, R is an intermediate router, and T is the TargNode. If the RREQ-DIO arrives over an interface that is known to be symmetric, and the 'S' bit is set to 1, then it remains as 1, as illustrated in Figure 4. If an intermediate router sends out RREQ-DIO with the 'S' bit set to 1, then all the one-hop links on the route from the OrigNode O to this router meet the requirements of route discovery, and the route can be used symmetrically.

```
                                  BR
                               /----+----\
                             /      |     \
                           /        |        \
                          R         R         R
                        _/  \       |        /  \
                       /     \      |       /     \
                      /       \     |      /       \
                    R -------- R --- R ----- R -------- R
                  /  \  <--S=1-->  / \   <--S=1-->  /  \
            <--S=1--> \           /   \           /   <--S=1-->
              /        \         /     \        /        \
            O ---------- R ------ R------ R ----- R ----------- T
           / \                 / \            / \         / \
          /   \               /   \          /   \       /   \
         /     \             /     \        /     \     /     \
        R ----- R ----------- R ----- R ----- R ----- R ---- R----- R

          >---- RREQ-Instance (Control: O-->T;  Data: T-->O) ------->
          <---- RREP-Instance (Control: T-->O;  Data: O-->T) -------<
```

Figure 4: AODV-RPL with Symmetric Paired Instances

Upon receiving a RREQ-DIO with the 'S' bit set to 1, a node determines whether this one-hop link can be used symmetrically, i.e., both the two directions meet the requirements of data transmission. If the RREQ-DIO arrives over an interface that is not known to be symmetric, or is known to be asymmetric, the 'S' bit is set to 0. If the 'S' bit arrives already set to be '0', it is set to be '0' on retransmission (Figure 5). Therefore, for asymmetric route, there is at least one hop which doesn't fulfill the constraints in the two directions. Based on the 'S' bit received in RREQ-DIO, the TargNode T determines whether or not the route is symmetric before transmitting the RREP-DIO message upstream towards the OrigNode O.

The criteria used to determine whether or not each link is symmetric is beyond the scope of the document, and may be implementation-specific. For instance, intermediate routers MAY use local information (e.g., bit rate, bandwidth, number of cells used in 6tisch), a priori knowledge (e.g. link quality according to previous communication) or use averaging techniques as appropriate to the application.

Appendix A describes an example method using the ETX and RSSI to estimate whether the link is symmetric in terms of link quality is given in using an averaging technique.

```
                                     BR
                                 /----+----\
                               /      |      \
                             /        |        \
                           R          R          R
                         / \          |        /   \
                       /     \        |       /      \
                     /         \      |      /         \
                    R --------- R --- R ---- R --------- R
                  /  \   --S=1-->   / \    --S=0-->   /   \
            --S=1-->   \           /    \            /   --S=0-->
             /          \        /       \         /         \
           O ---------- R ------ R------ R ----- R ----------- T
          / \                   / \             / \           / \
         /  <--S=0--           /   \           /   \         / <--S=0--
        /     \               /     \         /     \       /     \
       R ----- R ----------- R ----- R ----- R ----- R ---- R----- R
                   <--S=0--   <--S=0-- <--S=0-- <--S=0--    <--S=0--

       >---- RREQ-Instance (Control: O-->T;  Data: T-->O) ------->
       <---- RREP-Instance (Control: T-->O;  Data: O-->T) -------<
```

Figure 5: AODV-RPL with Asymmetric Paired Instances

6. AODV-RPL Operation

6.1. Route Request Generation

The route discovery process is initiated when an application at the OrigNode has data to be transmitted to the TargNode, but does not have a route for the target that fulfills the requirements of the data transmission. In this case, the OrigNode builds a local RPLInstance and a DODAG rooted at itself. Then it transmits a DIO message containing exactly one RREQ option (see Section 4.1) via link-local multicast. The DIO MUST contain at least one ART Option (see Section 4.3). The 'S' bit in RREQ-DIO sent out by the OrigNode is set to 1.

Each node maintains a sequence number, which rolls over like a lollipop counter [Perlman83]; refer to section 7.2 of [RFC6550] for detailed operation. When the OrigNode initiates a route discovery process, it MUST increase its own sequence number to avoid conflicts with previously established routes. The sequence number is carried in the OrigSeqNo field of the RREQ option.

The address in the ART Option can be a unicast IPv6 address or a prefix. The OrigNode can initiate the route discovery process for multiple targets simultaneously by including multiple ART Options,

and within a RREQ-DIO the requirements for the routes to different TargNodes MUST be the same.

OrigNode can maintain different RPLInstances to discover routes with different requirements to the same targets. Using the InstanceID pairing mechanism (see Section 6.3.3), route replies (RREP-DIOs) for different RPLInstances can be distinguished.

The transmission of RREQ-DIO obeys the Trickle timer. If the duration specified by the "L" bit has elapsed, the OrigNode MUST leave the DODAG and stop sending RREQ-DIOs in the related RPLInstance.

6.2. Receiving and Forwarding RREQ messages

6.2.1. General Processing

Upon receiving a RREQ-DIO, a router which does not belong to the RREQ-instance goes through the following steps:

Step 1:

If the 'S' bit in the received RREQ-DIO is set to 1, the router MUST check the two directions of the link by which the RREQ-DIO is received. In case that the downward (i.e. towards the TargNode) direction of the link can't fulfill the requirements, the link can't be used symmetrically, thus the 'S' bit of the RREQ-DIO to be sent out MUST be set as 0. If the 'S' bit in the received RREQ-DIO is set to 0, the router only checks into the upward direction (towards the OrigNode) of the link.

If the upward direction of the link can fulfill the requirements indicated in the constraint option, and the router's rank would not exceed the MaxRank limit, the router joins the DODAG of the RREQ-Instance. The router that transmitted the received RREQ-DIO is selected as the preferred parent. Later, other RREQ-DIO messages might be received. How to maintain the parent set, select the preferred parent, and update the router's rank obeys the core RPL and the OFs defined in ROLL WG. In case that the constraint or the MaxRank limit is not fulfilled, the router MUST discard the received RREQ-DIO and MUST NOT join the DODAG.

Step 2:

Then the router checks if one of its addresses is included in one of the ART Options. If so, this router is one of the TargNodes. Otherwise, it is an intermediate router.

Step 3:

If the 'H' bit is set to 1, then the router (TargNode or intermediate) MUST build the upward route entry accordingly. The route entry MUST include at least the following items: Source Address, InstanceID, Destination Address, Next Hop, Lifetime, and Sequence Number. The Destination Address and the InstanceID can be respectively learned from the DODAGID and the RPLInstanceID of the RREQ-DIO, and the Source Address is copied from the ART Option. The next hop is the preferred parent. The lifetime is set according to DODAG configuration and can be extended when the route is actually used. The sequence number represents the freshness of the route entry, and it is copied from the Orig SeqNo field of the RREQ option. A route entry with same source and destination address, same InstanceID, but stale sequence number, SHOULD be deleted.

If the 'H' bit is set to 0, an intermediate router MUST include the address of the interface receiving the RREQ-DIO into the address vector.

Step 4:

An intermediate router transmits a RREQ-DIO via link-local multicast. TargNode prepares a RREP-DIO.

6.2.2. Additional Processing for Multiple Targets

If the OrigNode tries to reach multiple TargNodes in a single RREQ-instance, one of the TargNodes can be an intermediate router to the others, therefore it SHOULD continue sending RREQ-DIO to reach other targets. In this case, before rebroadcasting the RREQ-DIO, a TargNode MUST delete the Target Option encapsulating its own address, so that downstream routers with higher ranks do not try to create a route to this TargetNode.

An intermediate router could receive several RREQ-DIOs from routers with lower ranks in the same RREQ-instance but have different lists of Target Options. When rebroadcasting the RREQ-DIO, the intersection of these lists SHOULD be included. For example, suppose two RREQ-DIOs are received with the same RPLInstance and OrigNode. Suppose further that the first RREQ has (T1, T2) as the targets, and the second one has (T2, T4) as targets. Then only T2 needs to be included in the generated RREQ-DIO. If the intersection is empty, it means that all the targets have been reached, and the router SHOULD NOT send out any RREQ-DIO. Any RREQ-DIO message with different ART Options coming from a router with higher rank is ignored.

6.3. Generating Route Reply (RREP) at TargNode

6.3.1. RREP-DIO for Symmetric route

If a RREQ-DIO arrives at TargNode with the 'S' bit set to 1, there is a symmetric route along which both directions can fulfill the requirements. Other RREQ-DIOs might later provide asymmetric upward routes (i.e. S=0). Selection between a qualified symmetric route and an asymmetric route that might have better performance is implementation-specific and out of scope. If the implementation uses the symmetric route, the TargNode MAY delay transmitting the RREP-DIO for duration RREP_WAIT_TIME to await a better symmetric route.

For a symmetric route, the RREP-DIO message is unicast to the next hop according to the accumulated address vector (H=0) or the route entry (H=1). Thus the DODAG in RREP-Instance does not need to be built. The RPLInstanceID in the RREP-Instance is paired as defined in Section 6.3.3. In case the 'H' bit is set to 0, the address vector received in the RREQ-DIO MUST be included in the RREP-DIO. TargNode increments its current sequence number and uses the incremented result in the Dest SeqNo in the ART option of the RREQ-DIO. The address of the OrigNode MUST be encapsulated in the ART Option and included in this RREP-DIO message.

6.3.2. RREP-DIO for Asymmetric Route

When a RREQ-DIO arrives at a TargNode with the 'S' bit set to 0, the TargNode MUST build a DODAG in the RREP-Instance rooted at itself in order to discover the downstream route from the OrigNode to the TargNode. The RREP-DIO message MUST be re-transmitted via link-local multicast until the OrigNode is reached or MaxRank is exceeded.

The settings of the fields in RREP option and ART option are the same as for the symmetric route, except for the 'S' bit.

6.3.3. RPLInstanceID Pairing

Since the RPLInstanceID is assigned locally (i.e., there is no coordination between routers in the assignment of RPLInstanceID), the tuple (OrigNode, TargNode, RPLInstanceID) is needed to uniquely identify a discovered route. The upper layer applications may have different requirements and they can initiate the route discoveries simultaneously. Thus between the same pair of OrigNode and TargNode, there can be multiple AODV-RPL instances. To avoid any mismatch, the RREQ-Instance and the RREP-Instance in the same route discovery MUST be paired somehow, e.g. using the RPLInstanceID.

When preparing the RREP-DIO, a TargNode could find the RPLInstanceID to be used for the RREP-Instance is already occupied by another RPL Instance from an earlier route discovery operation which is still active. In other words, it might happen that two distinct OrigNodes need routes to the same TargNode, and they happen to use the same RPLInstanceID for RREQ-Instance. In this case, the occupied RPLInstanceID MUST NOT be used again. Then the second RPLInstanceID MUST be shifted into another integer so that the two RREP-instances can be distinguished. In RREP option, the Shift field indicates the shift to be applied to original RPLInstanceID. When the new InstanceID after shifting exceeds 63, it rolls over starting at 0. For example, the original InstanceID is 60, and shifted by 6, the new InstanceID will be 2. Related operations can be found in Section 6.4.

6.4. Receiving and Forwarding Route Reply

Upon receiving a RREP-DIO, a router which does not belong to the RREQ-instance goes through the following steps:

Step 1:

If the 'S' bit is set to 1, the router proceeds to step 2.

If the 'S' bit of the RREP-DIO is set to 0, the router MUST check the downward direction of the link (towards the TargNode) over which the RREP-DIO is received. If the downward direction of the link can fulfill the requirements indicated in the constraint option, and the router's rank would not exceed the MaxRank limit, the router joins the DODAG of the RREP-Instance. The router that transmitted the received RREP-DIO is selected as the preferred parent. Afterwards, other RREP-DIO messages can be received. How to maintain the parent set, select the preferred parent, and update the router's rank obeys the core RPL and the OFs defined in ROLL WG.

If the constraints are not fulfilled, the router MUST NOT join the DODAG; the router MUST discard the RREQ-DIO, and does not execute the remaining steps in this section.

Step 2:

The router next checks if one of its addresses is included in the ART Option. If so, this router is the OrigNode of the route discovery. Otherwise, it is an intermediate router.

Step 3:

If the 'H' bit is set to 1, then the router (OrigNode or intermediate) MUST build a downward route entry. The route entry SHOULD include at least the following items: OrigNode Address, InstanceID, TargNode Address as destination, Next Hop, Lifetime and Sequence Number. For a symmetric route, the next hop in the route entry is the router from which the RREP-DIO is received. For an asymmetric route, the next hop is the preferred parent in the DODAG of RREQ-Instance. The InstanceID in the route entry MUST be the original RPLInstanceID (after subtracting the Shift field value). The source address is learned from the ART Option, and the destination address is learned from the DODAGID. The lifetime is set according to DODAG configuration and can be extended when the route is actually used. The sequence number represents the freshness of the route entry, and is copied from the Dest SeqNo field of the ART option of the RREP-DIO. A route entry with same source and destination address, same InstanceID, but stale sequence number, SHOULD be deleted.

If the 'H' bit is set to 0, for an asymmetric route, an intermediate router MUST include the address of the interface receiving the RREP-DIO into the address vector; for a symmetric route, there is nothing to do in this step.

Step 4:

If the receiver is the OrigNode, it can start transmitting the application data to TargNode along the path as provided in RREP-Instance, and processing for the RREP-DIO is complete. Otherwise, in case of an asymmetric route, the intermediate router transmits the RREP-DIO via link-local multicast. In case of a symmetric route, the RREP-DIO message is unicast to the next hop according to the address vector in the RREP-DIO (H=0) or the local route entry (H=1). The RPLInstanceID in the transmitted RREP-DIO is the same as the value in the received RREP-DIO. The local knowledge for the TargNode's sequence number SHOULD be updated.

7. Gratuitous RREP

In some cases, an Intermediate router that receives a RREQ-DIO message MAY transmit a "Gratuitous" RREP-DIO message back to OrigNode instead of continuing to multicast the RREQ-DIO towards TargNode. The intermediate router effectively builds the RREP-Instance on behalf of the actual TargNode. The 'G' bit of the RREP option is provided to distinguish the Gratuitous RREP-DIO (G=1) sent by the Intermediate node from the RREP-DIO sent by TargNode (G=0).

The gratuitous RREP-DIO can be sent out when an intermediate router R receives a RREQ-DIO for a TargNode T, and R happens to have a more

recent (larger destination sequence number) pair of downward and upward routes to T which also fulfill the requirements.

In case of source routing, the intermediate router R MUST unicast the received RREQ-DIO to TargNode T including the address vector between the OrigNode O and the router R. Thus T can have a complete upward route address vector from itself to O. Then R MUST send out the gratuitous RREP-DIO including the address vector from R to T.

In case of hop-by-hop routing, R MUST unicast the received RREQ-DIO hop-by-hop to T. The routers along the route SHOULD build new route entries with the related RPLInstanceID and DODAGID in the downward direction. Then T MUST unicast the RREP-DIO hop-by-hop to R, and the routers along the route SHOULD build new route entries in the upward direction. Upon receiving the unicast RREP-DIO, R sends the gratuitous RREP-DIO to the OrigNode as defined in Section 6.3.

8. Operation of Trickle Timer

The trickle timer operation to control RREQ-Instance/RREP-Instance multicast is similar to that in P2P-RPL [RFC6997].

9. IANA Considerations

9.1. New Mode of Operation: AODV-RPL

IANA is required to assign a new Mode of Operation, named "AODV-RPL" for Point-to-Point(P2P) hop-by-hop routing under the RPL registry. The value of TBD1 is assigned from the "Mode of Operation" space [RFC6550].

Value	Description	Reference
TBD1 (5)	AODV-RPL	This document

Figure 6: Mode of Operation

9.2. AODV-RPL Options: RREQ, RREP, and Target

Three entries are required for new AODV-RPL options "RREQ", "RREP" and "ART" with values of TBD2 (0x0A), TBD3 (0x0B) and TBD4 (0x0C) from the "RPL Control Message Options" space [RFC6550].

Value	Meaning	Reference
TBD2 (0x0A)	RREQ Option	This document
TBD3 (0x0B)	RREP Option	This document
TBD3 (0x0C)	ART Option	This document

Figure 7: AODV-RPL Options

10. Security Considerations

The security mechanisms defined in section 10 of [RFC6550] and section 11 of [RFC6997] can also be applied to the control messages defined in this specification. The RREQ-DIO and RREP-DIO both have a secure variant, which provide integrity and replay protection as well as optional confidentiality and delay protection.

AODV-RPL can operate in the three security modes defined in [RFC6550]. AODV-RPL messages SHOULD use a security mode at least as strong as the security mode used in RPL.

- o Unsecured. In this mode, RREQ-DIO and RREP-DIO are used without any security fields as defined in section 6.1 of [RFC6550]. The control messages can be protected by other security mechanisms, e.g. link-layer security. This mode SHOULD NOT be used when RPL is using Preinstalled mode or Authenticated mode (see below).

- o Preinstalled. In this mode, AODV-RPL uses secure RREQ-DIO and RREP-DIO messages, and a node wishing to join a secured network will have been pre-configured with a shared key. A node can use that key to join the AODV-RPL DODAG as a host or a router. Unsecured messages MUST be dropped. This mode SHOULD NOT be used when RPL is using Authenticated mode.

- o Authenticated. In this mode, besides the preinstalled shared key, a node MUST obtain a second key from a key authority. The interaction between a node and the key authority is out of scope for this specification. Authenticated mode may be useful, for instance, to protect against a malicious rogue router advertising false information in RREQ-DIO or RREP-DIO to include itself in the discovered route. This mode would also prevent a malicious router from initiating route discovery operations or launching denial-of-service attacks to impair the performance of the LLN. AODV-RPL can use the keys established with the Authenticated mode RPL instance. Once a router or a host has been authenticated in the

RPL instance, it can join the AODV-RPL instance without any further authentication. The authentication in AODV-RPL can also be independent to RPL if, before joining the AODV-RPL instance, the node obtains another key from the key authority.

11. Future Work

There has been some discussion about how to determine the initial state of a link after an AODV-RPL-based network has begun operation. The current draft operates as if the links are symmetric until additional metric information is collected. The means for making link metric information is considered out of scope for AODV-RPL. In the future, RREQ and RREP messages could be equipped with new fields for use in verifying link metrics. In particular, it is possible to identify unidirectional links; an RREQ received across a unidirectional link has to be dropped, since the destination node cannot make use of the received DODAG to route packets back to the source node that originated the route discovery operation. This is roughly the same as considering a unidirectional link to present an infinite cost metric that automatically disqualifies it for use in the reverse direction.

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Appendix A. Example: ETX/RSSI Values to select S bit

We have tested the combination of "RSSI(downstream)" and "ETX (upstream)" to determine whether the link is symmetric or asymmetric at the intermediate nodes. The example of how the ETX and RSSI values are used in conjuction is explained below:

```
Source---------->NodeA---------->NodeB------->Destination
```

Figure 8: Communication link from Source to Destination

RSSI at NodeA for NodeB	Expected ETX at NodeA for NodeB->NodeA
> -60	150
-70 to -60	192
-80 to -70	226
-90 to -80	662
-100 to -90	993

Table 1: Selection of 'S' bit based on Expected ETX value

We tested the operations in this specification by making the following experiment, using the above parameters. In our experiment, a communication link is considered as symmetric if the ETX value of NodeA->NodeB and NodeB->NodeA (See Figure.8) are, say, within 1:3 ratio. This ratio should be taken as a notional metric for deciding link symmetric/asymmetric nature, and precise definition of the ratio is beyond the scope of the draft. In general, NodeA can only know the ETX value in the direction of NodeA -> NodeB but it has no direct way of knowing the value of ETX from NodeB->NodeA. Using physical testbed experiments and realistic wireless channel propagation models, one can determine a relationship between RSSI and ETX representable as an expression or a mapping table. Such a relationship in turn can be used to estimate ETX value at nodeA for link NodeB--->NodeA from the received RSSI from NodeB. Whenever nodeA determines that the link towards the nodeB is bi-directional asymmetric then the "S" bit is set to "S=0". Later on, the link from NodeA to Destination is asymmetric with "S" bit remains to "0".

Appendix B. Changelog

B.1. Changes from version 05 to version 06

- Added Security Considerations based on the security mechanisms defined in RFC 6550.

- Clarified the nature of improvements due to P2P route discovery versus bidirectional asymmetric route discovery.

- Editorial improvements and corrections.

B.2. Changes from version 04 to version 05

- Add description for sequence number operations.

- Extend the residence duration L in section 4.1.

- Change AODV-RPL Target option to ART option.

B.3. Changes from version 03 to version 04

- Updated RREP option format. Remove the 'T' bit in RREP option.

- Using the same RPLInstanceID for RREQ and RREP, no need to update [RFC6550].

- Explanation of Shift field in RREP.

- Multiple target options handling during transmission.

B.4. Changes from version 02 to version 03

- Include the support for source routing.

- Import some features from [RFC6997], e.g., choice between hop-by-hop and source routing, the "L" bit which determines the duration of residence in the DAG, MaxRank, etc.

- Define new target option for AODV-RPL, including the Destination Sequence Number in it. Move the TargNode address in RREQ option and the OrigNode address in RREP option into ADOV-RPL Target Option.

- Support route discovery for multiple targets in one RREQ-DIO.

- New InstanceID pairing mechanism.

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