ROLL S. Anamalamudi
Internet-Draft Huaiyin Institute of Technology
Intended status: Standards Track M. Zhang
Expires: September 6, 2018 Huawei Technologies
AR. Sangi
Huaiyin Institute of Technology
C. Perkins
Futurewei
S.V.R.Anand
Indian Institute of Science
B. Liu
Huawei Technologies
March 5, 2018

Asymmetric AODV-P2P-RPL in Low-Power and Lossy Networks (LLNs)
draft-ietf-roll-aodv-rpl-03

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.

Copyright Notice

Table of Contents

1. Introduction

RPL[RFC6550] is a IPv6 distance vector routing protocol for Low-power and Lossy Networks (LLNs), and is 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 sub-optimal routes and may suffer severe congestion near the DAG root [RFC6997], [RFC6998].

To discover optimal 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 (TargNode). TargNode 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 TargNode subsequently replies to the source along the established forward route, receiving nodes determine the next hop towards TargNode. In other words, it is efficient to use only routing tables for P2P-RDO message instead of "Address vector" for hop-by-hop routes (H=1) over symmetric links.

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 eliminates the possibility to use 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] describes 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, which can achieve higher route diversity. AODV-RPL eliminates the need for address vector control 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].

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]. Additionally, 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. If the OrigNode doesn't require an upward route towards itself, the route is also considered as asymmetric.

Bi-directional Asymmetric Link
: A link that can be used in both directions but with different link characteristics.

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.

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 of an application.

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

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
The 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. Both directions fulfill the constraints in route discovery.

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.

3. Overview of AODV-RPL

With AODV-RPL, routes from OrigNode to TargNode within the LLN network established are "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 point-to-point; in other words the routes are not constrained to traverse a common ancestor. Unlike core 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, route discovery is initiated by forming a temporary DAG rooted at the OrigNode. Paired DODAGs (Instances) are constructed according to a new 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 (as shown in Figure 4). 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. Similarly, the RREP-DIO message means the AODV-RPL mode DIO message from TargNode to OrigNode, containing the RREP option. Subsequently, the route discovered in the RREQ-Instance is used for data transmission from TargNode to OrigNode, and the route discovered in RREP-Instance is used for Data transmission from OrigNode to TargNode.

4. AODV-RPL DIO Options

4.1. AODV-RPL DIO RREQ Option

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 of the RREQ-Instance message:

Type

The type of the RREQ option(see Section 9.2).

Option Length

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 issuing this RREQ-DIO. The bit SHOULD be set to 1 in the RREQ-DIO when the OrigNode initiates the route discovery.

X

Reserved.

H

The OrigNode sets this flag to one if it desires a hop-by-hop route. It sets this flag to zero if it desires a source route. This flag is valid to both downstream route and upstream route.

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.

L

2-bit unsigned integer. This field indicates the duration that a node joining 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 detailed definition can be found in [RFC6997].

* 0x00: No duration time imposed.
* 0x01: 2 seconds
* 0x02: 16 seconds
* 0x03: 64 seconds

It should be indicated here that L is not 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. A node MUST NOT join a temporary DODAG if its own rank would equal to or higher than the limit. A value of 0 in this field indicates the limit is infinity. For more details please refer to [RFC6997].

OrigNode Sequence Number

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

Address Vector (Optional)

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.

4.2. AODV-RPL DIO RREP Option

A RREP-DIO message MUST carry exactly one RREP option.

The 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 |H|X| Compr | L |   MaxRank     |
       +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
       |T|G|  SHIFT    |    Reserved   |                               |
       +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+                               |
       |                                                               |
       |                                                               |
       |         Address Vector (Optional, Variable Length)            |
       .                                                               .
       .                                                               .
       +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

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

Type
The type of the RREP option (see Section 9.2)

Option Length
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.

H
This bit indicates the downstream route is source routing (H=0) or hop-by-hop (H=1). It SHOULD 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 with the same definition as in Section 4.1.

MaxRank
Same definition as in RREQ option.

T
'T' is set to 1 to indicate that the RREP-DIO MUST include exactly one AODV-RPL Target Option. Otherwise, the Target Option is not necessary in the RREP-DIO.

G

Gratuitous route (see Section 7).

SHIFT
6-bit unsigned integer. This field indicates the how many the original InstanceID (see Section 6.3.3) is shifted (added an integer from 0 to 63). 0 indicates that the original InstanceID is used.

Reserved
Reserved for future usage; MUST be initialized to zero and MUST be ignored upon reception.

Address Vector (Optional)
It is only present when the 'H' bit is set to 0. For an asymmetric route, it is a vector of IPv6 addresses representing the route that the RREP-DIO has passed. For symmetric route, it is the accumulated vector when the RREQ-DIO arrives at the TargNode.

4.3. AODV-RPL DIO Target Option

The AODV-RPL Target 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 AODV-RPL Target Options. A RREP-DIO message MUST carry exactly one AODV-RPL Target Option encapsulating the address of the OrigNode if the 'T' bit is set to 1.

If an OrigNode want to discover routes to multiple TargNodes, and these routes share the same constraints, then the OrigNode can include all the addresses of the TargNodes into multiple AODV-RPL Target Options in the RREQ-DIO, so that the cost can be reduced to building only one DODAG. Different addresses of the TargNodes can merge if they share the same prefix.

```
 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 of the AODV-RPL Target Option (see Section 9.2)

Destination Sequence Number

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 BorderRouter, 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. An intermediate router sends out RREQ-DIO with the 'S' bit set to 1, meaning that all the one-hop links on the route from the OrigNode to this router meet the requirements of route discovery; thus 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: S-->D;  Data: D-->S) ------->
         <---- RREP-Instance (Control: D-->S;  Data: S-->D) -------<
```

Figure 4: AODV-RPL with Symmetric Paired Instances

Upon receiving a RREQ-DIO with the 'S' bit set to 1, a node MUST decide if 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. Moreover, 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 decides whether or not the route is symmetric before transmitting the RREP-DIO message upstream towards the OrigNode.

The criterion and the corresponding metric used to determine if a one-hop link is symmetric or not is implementation specific and beyond the scope of the document. Also, the difference in the metric values for upward and downward directions of a link that can be establish its symmetric and asymmetric nature is implementation specific. For instance, the intermediate routers MAY choose to 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 estimate the metric using averaging techniques or any other means that is appropriate to the application context.

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: S-->D;  Data: D-->S) ------->
       <---- RREP-Instance (Control: D-->S;  Data: S-->D) -------<
```

Figure 5: AODV-RPL with Asymmetric Paired Instances

6. AODV-RPL Operation

6.1. Generating Route Request at OrigNode

The route discovery process is initiated on-demand when an application at the OrigNode has data to be transmitted to the TargNode, but no route for the target exists or the current routes don't fulfill the requirements of the data transmission. In this case, the OrigNode MUST build a local RPLInstance and a DODAG rooted at itself. Then it begins to send out DIO message in AODV-RPL MoP via link-local multicast. The DIO MUST contain exactly one RREQ option as defined in Section 4.1, and at least one AODV-RPL Target Option as defined in Figure 3. This DIO message is noted as RREQ-DIO. The 'S' bit in RREQ-DIO sent out by the OrigNode is set as 1.

The maintenance of Originator and Destination Sequence Number in the RREQ option is as defined in AODV [RFC3561].

The address in the AODV-RPL Target Option can be a unicast IPv6 address, a prefix or a multicast address. The OrigNode can initiate

the route discovery process for multiple targets simultaneously by including multiple AODV-RPL Target Options, and within a RREQ-DIO the requirements for the routes to different TargNodes MUST be the same.

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

The transmission of RREQ-DIO follows the Trickle timer. When the L duration has transpired, the OrigNode MUST leave the DODAG and stop sending any RREQ-DIOs in the related RPLInstance.

6.2. Receiving and Forwarding Route Request

Upon receiving a RREQ-DIO, a router out of 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 look into 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, then the link can't be used symmetrically, thus the 'S' bit of the RREQ-DIO to be send out MUST be set as 0. If the 'S' bit in the received RREQ-DIO is set to 0, the router MUST look only into the upward direction (i.e. 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 be inferior to the MaxRank limit, the router chooses to join in the DODAG of the RREQ-Instance. The router issuing the received RREQ-DIO is selected as the preferred parent. Afterwards, other RREQ-DIO message can be received. How to maintain the parent set, select the preferred parent, and update the router's rank follows 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 NOT join in the DODAG. Otherwise, go to the following steps 2, 3, 4 and 5.

A router MUST discard a received RREQ-DIO if the advertised rank equals or exceeds the MaxRank limit.

Step 2:

Then the router checks if one of its addresses is included in one of the AODV-RPL Target Options or belongs to the indicated

multicast group. 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 route entry towards its preferred parent. The route entry SHOULD be stored along with the associated RPLInstanceID and DODAGID. 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:

If there are multiple AODV-RPL Target Options in the received RREQ-DIO, a TargNode SHOULD continue sending RREQ-DIO to reach other targets. When preparing its own RREQ-DIO, the TargNode MUST delete the AODV-RPL Target Option related to its own address, so that the routers which higher ranks would know the route to this target has already been found. When an intermediate router receives several RREQ-DIOs which include different lists of AODV-RPL Target Options, the intersection of these lists will be included in its own RREQ-DIO. If the intersection is empty, the router SHOULD NOT send out any RREQ-DIO. Any RREQ-DIO message with different AODV-RPL Target Options coming from a router with higher rank is ignored.

Step 5:

For an intermediate router, it sends out its own RREQ-DIO via link-local multicast. For a TargNode, it can begin to prepare the RREP-DIO.

6.3. Generating Route Reply at TargNode

6.3.1. RREP-DIO for Symmetric route

When a RREQ-DIO arrives at a TargNode with the 'S' bit set to 1, it means there exists a symmetric route in which the two directions can fulfill the requirements. Other RREQ-DIOs can bring the upward direction of asymmetric routes (i.e. S=0). How to choose between a qualified symmetric route and an asymmetric route hopefully having better performance is implementation-specific and out of scope. If the implementation choose to use the symmetric route, the TargNode MAY send out the RREP-DIO after a duration RREP_WAIT_TIME to wait for the convergence of RD to an optimal symmetric route.

For symmetric route, the RREP-DIO message is sent via unicast to the OrigNode; therefore the DODAG in RREP-Instance doesn't need to be actually built. The RPLInstanceID in the RREP-Instance is paired as defined in Section 6.3.3. The 'S' bit in the base DIO remains as 1. In the RREP option, The 'SHIFT' field and the 'T' bit are set as defined in Section 6.3.3. The address vector received in the RREQ-DIO MUST be included in this RREP option in case the 'H' bit is set to 0 (both in RREQ-DIO and RREP-DIO). If the 'T' bit is set to 1, the address of the OrigNode MUST be encapsulated in an AODV-RPL Target Option and included in this RREP-DIO message, and the Destination Sequence Number is set according to AODV [RFC3561].

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 send out via link-local multicast until the OrigNode is reached or the MaxRank limit is exceeded.

The settings of the RREP-DIO are the same as in symmetric route.

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 (RPLInstanceID, DODAGID, Address in the AODV-RPL Target Option) is needed to uniquely identify a DODAG in an AODV-RPL instance. Between the OrigNode and the TargNode, there can be multiple AODV-RPL instances when applications upper layer have different requirements. Therefore the RREQ-Instance and the RREP-Instance in the same route discovery MUST be paired. The way to realize this is to pair their RPLInstance IDs.

Typically, the two InstanceIDs are set as the local InstanceID in core RPL:

```
                0 1 2 3 4 5 6 7
               +-+-+-+-+-+-+-+-+
               |1|D|    ID     |  Local RPLInstanceID in 0..63
               +-+-+-+-+-+-+-+-+
```

Figure 6: Local Instance ID

The first bit is set to 1 indicating the RPLInstanceID is local. The 'D' bit here is used to distinguish the two AODV-RPL instances: D=0 for RREQ-Instance, D=1 for RREP-Instance. The ID of 6 bits SHOULD be

the same for RREQ-Instance and RREP-Instance. Here, the 'D' bit is used slightly differently than in RPL.

When preparing the RREP-DIO, a TargNode could find the RPLInstanceID to be used for the RREP-Instance is already occupied by another instance from an earlier route discovery operation which is still active. In other words, two 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 this RPLInstanceID SHOULD be shifted into another integer and shifted back to the original one at the OrigNode. In RREP option, the SHIFT field indicates the how many the original RPLInstanceID is shifted. When the new InstanceID after shifting exceeds 63, it will come back counting from 0. For example, the original InstanceID is 60, and shifted by 6, the new InstanceID will be 2. The 'T' MUST be set to 1 to make sure the two RREP-DIOs can be distinguished by the address of the OrigNode in the AODV-RPL Target Option.

6.4. Receiving and Forwarding Route Reply

Upon receiving a RREP-DIO, a router out of the RREP-Instance goes through the following steps:

Step 1:

If the 'S' bit of the RREP-DIO is set to 0, the router MUST look into the downward direction of the link (towards the TargNode) by 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 be inferior to the MaxRank limit, the router chooses to join in the DODAG of the RREP-Instance. The router issuing the received RREP-DIO is selected as the preferred parent. Afterwards, other RREQ-DIO messages can be received. How to maintain the parent set, select the preferred parent, and update the router's rank follows the core RPL and the OFs defined in ROLL WG.

If the constraints are not fulfilled, the router MUST NOT join in the DODAG, and will not go through steps 2, 3, and 4.

A router MUST discard a received RREQ-DIO if the advertised rank equals or exceeds the MaxRank limit.

If the 'S' bit is set to 1, the router does nothing in this step.

Step 2:

Then the router checks if one of its addresses is included in the AODV-RPL Target 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 route entry including the RPLInstanceID of RREP-Instance and the DODAGID. For symmetric route, the route entry is to the router from which the RREP-DIO is received. For asymmetric route, the route entry is to the preferred parent in the DODAG of RREQ-Instance.

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

Step 4:

For an intermediate router, in case of asymmetric route, the RREP-DIO is sent out via link-local multicast; in case of symmetric route, the RREP-DIO is unicasted to the OrigNode via the next hop in source routing (H=0), or via the next hop in the route entry built in the RREQ-Instance (H=1). For the OrigNode, it can start transmitting the application data to TargNode along the path as discovered through RREP-Instance.

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 both forward and reverse 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 address vector between O and itself. Then T MUST unicast a RREP-DIO including the address vector between T and R.

In case of hop-by-hop routing, R MUST unicast the received RREQ-DIO 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 to R, and the routers along the route SHOULD build new route entries in the upward direction. Upon received the unicast RREP-DIO, R sends the gratuitous RREP-DIO to the OrigNode as the same way 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 7: Mode of Operation

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

Three entries are required for new AODV-RPL options "RREQ", "RREP" and "AODV-RPL Target" 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)	AODV-RPL Target Option	This document

Figure 8: AODV-RPL Options

10. Security Considerations

This document does not introduce additional security issues compared to base RPL. For general RPL security considerations, see [RFC6550].

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.

12. References

12.1. 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>.

[RFC3561] Perkins, C., Belding-Royer, E., and S. Das, "Ad hoc On-Demand Distance Vector (AODV) Routing", RFC 3561, DOI 10.17487/RFC3561, July 2003, <https://www.rfc-editor.org/info/rfc3561>.

[RFC5548] Dohler, M., Ed., Watteyne, T., Ed., Winter, T., Ed., and D. Barthel, Ed., "Routing Requirements for Urban Low-Power and Lossy Networks", RFC 5548, DOI 10.17487/RFC5548, May 2009, <https://www.rfc-editor.org/info/rfc5548>.

[RFC5673] Pister, K., Ed., Thubert, P., Ed., Dwars, S., and T. Phinney, "Industrial Routing Requirements in Low-Power and Lossy Networks", RFC 5673, DOI 10.17487/RFC5673, October 2009, <https://www.rfc-editor.org/info/rfc5673>.

[RFC5826] Brandt, A., Buron, J., and G. Porcu, "Home Automation Routing Requirements in Low-Power and Lossy Networks", RFC 5826, DOI 10.17487/RFC5826, April 2010, <https://www.rfc-editor.org/info/rfc5826>.

[RFC5867] Martocci, J., Ed., De Mil, P., Riou, N., and W. Vermeylen, "Building Automation Routing Requirements in Low-Power and Lossy Networks", RFC 5867, DOI 10.17487/RFC5867, June 2010, <https://www.rfc-editor.org/info/rfc5867>.

[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>.

[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>.

[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>.

[RFC6998] Goyal, M., Ed., Baccelli, E., Brandt, A., and J. Martocci, "A Mechanism to Measure the Routing Metrics along a Point-to-Point Route in a Low-Power and Lossy Network", RFC 6998, DOI 10.17487/RFC6998, August 2013, <https://www.rfc-editor.org/info/rfc6998>.

12.2. Informative References

[I-D.thubert-roll-asymlink] Thubert, P., "RPL adaptation for asymmetrical links", draft-thubert-roll-asymlink-02 (work in progress), December 2011.

Appendix A. ETX/RSSI Values to select S bit

We have tested the combination of "RSSI(downstream)" and "ETX (upstream)" to decide 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 9: Communication link from Source to Destination

RSSI at NodeA for NodeB	Expected ETX at NodeA for NodeB->NodeA
> -15	150
-25 to -15	192
-35 to -25	226
-45 to -35	662
-55 to -45	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. Changes to version 02

- o Include the support for source routing.
- o Bring some features from [RFC6997], e.g., choice between hop-by-hop and source routing, duration of residence in the DAG, MaxRank, etc.
- o 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.
- o Support route discovery for multiple targets in one RREQ-DIO.

o New InstanceID pairing mechanism.

Authors' Addresses

Satish Anamalamudi
Huaiyin Institute of Technology
No.89 North Beijing Road, Qinghe District
Huaian 223001
China

Email: satishnaidu80@gmail.com

Mingui Zhang
Huawei Technologies
No. 156 Beiqing Rd. Haidian District
Beijing 100095
China

Email: zhangmingui@huawei.com

Abdur Rashid Sangi
Huaiyin Institute of Technology
No.89 North Beijing Road, Qinghe District
Huaian 223001
P.R. China

Email: sangi_bahrian@yahoo.com

Charles E. Perkins
Futurewei
2330 Central Expressway
Santa Clara 95050
Unites States

Email: charliep@computer.org

S.V.R Anand
Indian Institute of Science
Bangalore 560012
India

Email: anand@ece.iisc.ernet.in

Bing Liu
Huawei Technologies
No. 156 Beiqing Rd. Haidian District
Beijing 100095
China

Email: remy.liubing@huawei.com