
Stream: Internet Engineering Task Force (IETF)
RFC: [0000](#)
Category: Standards Track
Published: August 2019
ISSN: 2070-1721
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Efficient Route Invalidation

Abstract

This document explains the problems associated with the current use of NPDAO messaging and also discusses the requirements for an optimized route invalidation messaging scheme. Further a new proactive route invalidation message called as "Destination Cleanup Object" (DCO) is specified which fulfills requirements of an optimized route invalidation messaging.

Status of This Memo

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Authors' Addresses

1. Introduction

RPL [RFC6550] (Routing Protocol for Low power and lossy networks) specifies a proactive distance-vector based routing scheme. RPL has optional messaging in the form of DAO (Destination Advertisement Object) messages, which the 6LBR (6Lo Border Router) and 6LR (6Lo Router) can use to learn a route towards the downstream nodes. In storing mode, DAO messages would result in routing entries being created on all intermediate 6LRs from the node's parent all the way towards the 6LBR.

RPL allows the use of No-Path DAO (NPDAO) messaging to invalidate a routing path corresponding to the given target, thus releasing resources utilized on that path. A NPDAO is a DAO message with route lifetime of zero, originates at the target node and always flows upstream towards the 6LBR. This document explains the problems associated with the current use of NPDAO messaging and also discusses the requirements for an optimized route invalidation messaging scheme. Further a new proactive route invalidation message called as "Destination Cleanup Object" (DCO) is specified which fulfills requirements of an optimized route invalidation messaging.

The document only caters to the RPL's storing mode of operation (MOP). The non-storing MOP does not require use of NPDAO for route invalidation since routing entries are not maintained on 6LRs.

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.

This specification requires readers to be familiar with all the terms and concepts that are discussed in "RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks" [[RFC6550](#)].

Low Power and Lossy Networks (LLN):

Network in which both the routers and their interconnect are constrained. LLN routers typically operate with constraints on processing power, memory, and energy (battery power). Their interconnects are characterized by high loss rates, low data rates, and instability.

6LoWPAN Router (6LR):

An intermediate router that is able to send and receive Router Advertisements (RAs) and Router Solicitations (RSs) as well as forward and route IPv6 packets.

Directed Acyclic Graph (DAG):

A directed graph having the property that all edges are oriented in such a way that no cycles exist.

Destination-Oriented DAG (DODAG):

A DAG rooted at a single destination, i.e., at a single DAG root with no outgoing edges.

6LoWPAN Border Router (6LBR):

A border router which is a DODAG root and is the edge node for traffic flowing in and out of the 6LoWPAN network.

Destination Advertisement Object (DAO):

DAO messaging allows downstream routes to the nodes to be established.

DODAG Information Object (DIO):

DIO messaging allows upstream routes to the 6LBR to be established. DIO messaging is initiated at the DAO root.

Common Ancestor node

6LR/6LBR node which is the first common node between two paths of a target node.

No-Path DAO (NPDAO):

A DAO message which has target with lifetime 0 used for the purpose of route invalidation.

Destination Cleanup Object (DCO):

A new RPL control message code defined by this document. DCO messaging improves proactive route invalidation in RPL.

Regular DAO:

A DAO message with non-zero lifetime. Routing adjacencies are created or updated based on this message.

Target node:

The node switching its parent whose routing adjacencies are updated (created/removed).

1.2. Current NPDAO messaging

RPL uses NPDAO messaging in the storing mode so that the node changing its routing adjacencies can invalidate the previous route. This is needed so that nodes along the previous path can release any resources (such as the routing entry) they maintain on behalf of target node.

For the rest of this document consider the following topology:

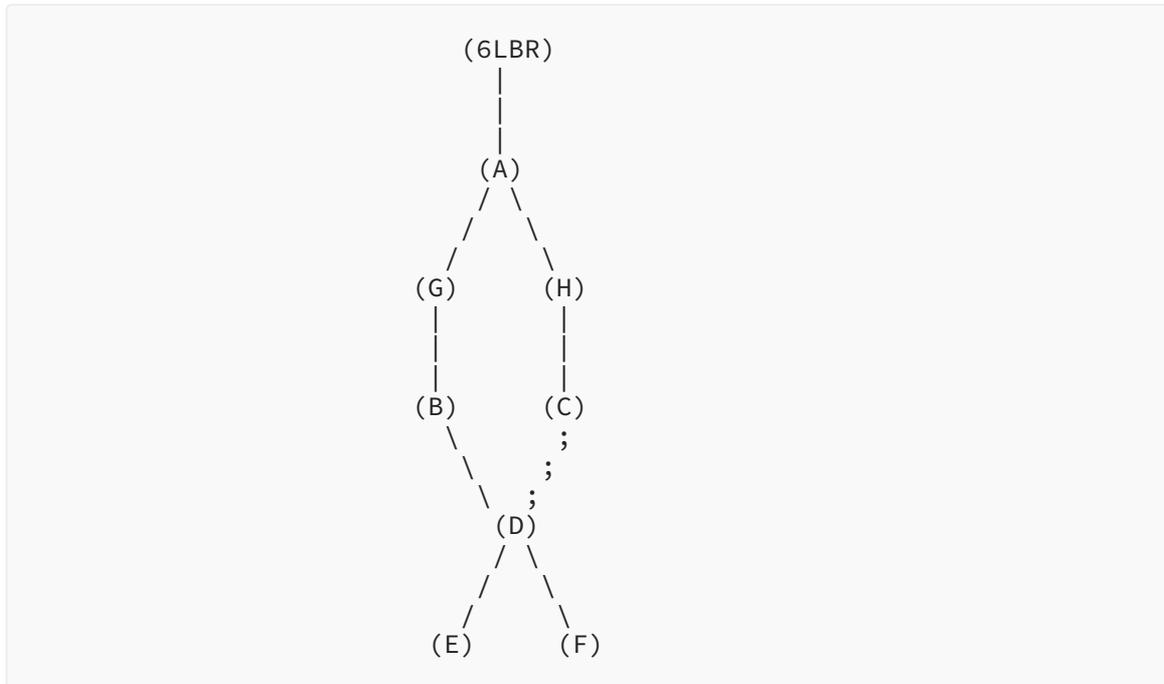


Figure 1: Sample topology

Node (D) is connected via preferred parent (B). (D) has an alternate path via (C) towards the 6LBR. Node (A) is the common ancestor for (D) for paths through (B)-(G) and (C)-(H). When (D) switches from (B) to (C), RPL allows sending NPDAO to (B) and regular DAO to (C).

1.3. Why Is NPDAO Important?

Nodes in LLNs may be resource constrained. There is limited memory available and routing entry records are one of the primary elements occupying dynamic memory in the nodes. Route invalidation helps 6LR nodes to decide which entries could be discarded to better optimize resource utilization. Thus it becomes necessary to have an efficient route invalidation mechanism. Also note that a single parent switch may result in a "sub-tree" switching from one parent to another. Thus the route invalidation needs to be done on behalf of the sub-tree and not the switching node alone. In the above example, when Node (D) switches parent, the route updates needs to be done for the routing tables entries of (C),(H),(A),(G), and (B) with destination (D),(E) and (F). Without efficient route invalidation, a 6LR may have to hold a lot of stale route entries.

2. Problems with current NPDAO messaging

2.1. Lost NPDAO due to link break to the previous parent

When a node switches its parent, the NPDAO is to be sent to its previous parent and a regular DAO to its new parent. In cases where the node switches its parent because of transient or permanent parent link/node failure then the NPDAO message is bound to fail.

2.2. Invalidate Routes of Dependent Nodes

RPL does not specify how route invalidation will work for dependent nodes rooted at the switching node, resulting in stale routing entries of the dependent nodes. The only way for 6LR to invalidate the route entries for dependent nodes would be to use route lifetime expiry which could be substantially high for LLNs.

In the example topology, when Node (D) switches its parent, Node (D) generates an NPDAO on its behalf. There is no NPDAO generated by the dependent child nodes (E) and (F), through the previous path via (D) to (B) and (G), resulting in stale entries on nodes (B) and (G) for nodes (E) and (F).

2.3. Possible route downtime caused by asynchronous operation of NPDAO and DAO

A switching node may generate both an NPDAO and DAO via two different paths at almost the same time. There is a possibility that an NPDAO generated may invalidate the previous route and the regular DAO sent via the new path gets lost on the way. This may result in route downtime impacting downward traffic for the switching node.

In the example topology, consider Node (D) switches from parent (B) to (C). An NPDAO sent via the previous route may invalidate the previous route whereas there is no way to determine whether the new DAO has successfully updated the route entries on the new path.

3. Requirements for the NPDAO Optimization

3.1. Req#1: Remove messaging dependency on link to the previous parent

When the switching node sends the NPDAO message to the previous parent, it is normal that the link to the previous parent is prone to failure (that's why the node decided to switch). Therefore, it is required that the route invalidation does not depend on the previous link which is prone to failure. The previous link referred here represents the link between the node and its previous parent (from whom the node is now disassociating).

3.2. Req#2: Dependent nodes route invalidation on parent switching

It should be possible to do route invalidation for dependent nodes rooted at the switching node.

3.3. Req#3: Route invalidation should not impact data traffic

While sending the NPDAO and DAO messages, it is possible that the NPDAO successfully invalidates the previous path, while the newly sent DAO gets lost (new path not set up successfully). This will result in downstream unreachability to the node switching paths. Therefore, it is desirable that the route invalidation is synchronized with the DAO to avoid the risk of route downtime.

4. Changes to RPL signaling

4.1. Change in RPL route invalidation semantics

As described in [Section 1.2](#), the NPDAO originates at the node changing to a new parent and traverses upstream towards the root. In order to solve the problems as mentioned in [Section 2](#), the document adds a new proactive route invalidation message called "Destination Cleanup Object" (DCO) that originates at a common ancestor node and flows downstream between the new and old path. The common ancestor node generates a DCO in response to the change in the next-hop on receiving a regular DAO with updated Path Sequence for the target.

The 6LRs in the path for DCO take action such as route invalidation based on the DCO information and subsequently send another DCO with the same information downstream to the next hop. This operation is similar to how the DAOs are handled on intermediate 6LRs in storing MOP in [\[RFC6550\]](#). Just like DAO in storing MOP, the DCO is sent using link-local unicast source and destination IPv6 address. Unlike DAO, which always travels upstream, the DCO always travels downstream.

In [Figure 1](#), when node D decides to switch the path from B to C, it sends a regular DAO to node C with reachability information containing the address of D as the target and an incremented Path Sequence. Node C will update the routing table based on the reachability information in the DAO and in turn generate another DAO with the same reachability information and forward it to H. Node H also follows the same procedure as Node C and forwards it to node A. When node A receives the regular DAO, it finds that it already has a routing table entry on behalf of the target address of node D. It finds however that the next hop information for reaching node D has changed i.e., node D has decided to change the paths. In this case, Node A which is the common ancestor node for node D along the two paths (previous and new), should generate a DCO which traverses downwards in the network. Node A handles normal DAO forwarding to 6LBR as required by [\[RFC6550\]](#).

4.2. Transit Information Option changes

Every RPL message is divided into base message fields and additional Options as described in [Section 6](#) of [\[RFC6550\]](#)

This document specifies a change in the Transit Information Option to contain the "Invalidate previous route" (I) flag. This I-flag signals the common ancestor node to generate a DCO on behalf of the target node. The I-flag is carried in the Transit Information Option which augments the reachability information for a given set of RPL Target(s). Transit Information Option with I-flag set should be carried in the DAO message when route invalidation is sought for the corresponding target(s).

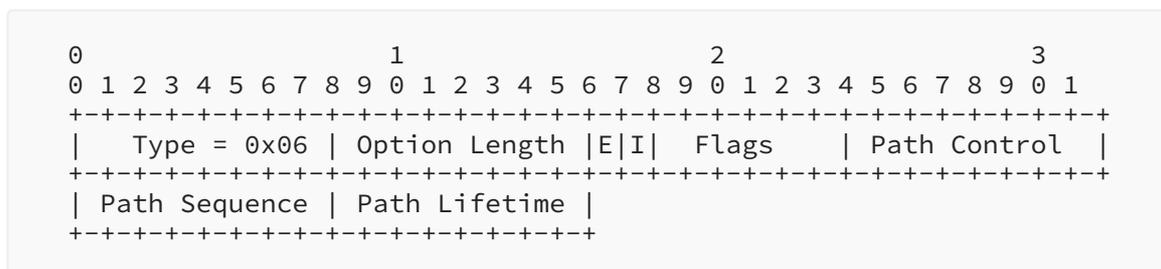


Figure 2: Updated Transit Information Option (New I flag added)

I (Invalidate previous route) flag:

The 'I' flag is set by the target node to indicate to the common ancestor node that it wishes to invalidate any previous route between the two paths.

[\[RFC6550\]](#) allows the parent address to be sent in the Transit Information Option depending on the mode of operation. In case of storing mode of operation the field is usually not needed. In case of DCO, the parent address field **MUST NOT** be included.

The common ancestor node **SHOULD** generate a DCO message in response to this I-flag when it sees that the routing adjacencies have changed for the target. The I-flag is intended to give the target node control over its own route invalidation, serving as a signal to request DCO generation.

4.3. Destination Cleanup Object (DCO)

A new ICMPv6 RPL control message code is defined by this specification and is referred to as "Destination Cleanup Object" (DCO), which is used for proactive cleanup of state and routing information held on behalf of the target node by 6LRs. The DCO message always traverses downstream and cleans up route information and other state information associated with the given target.

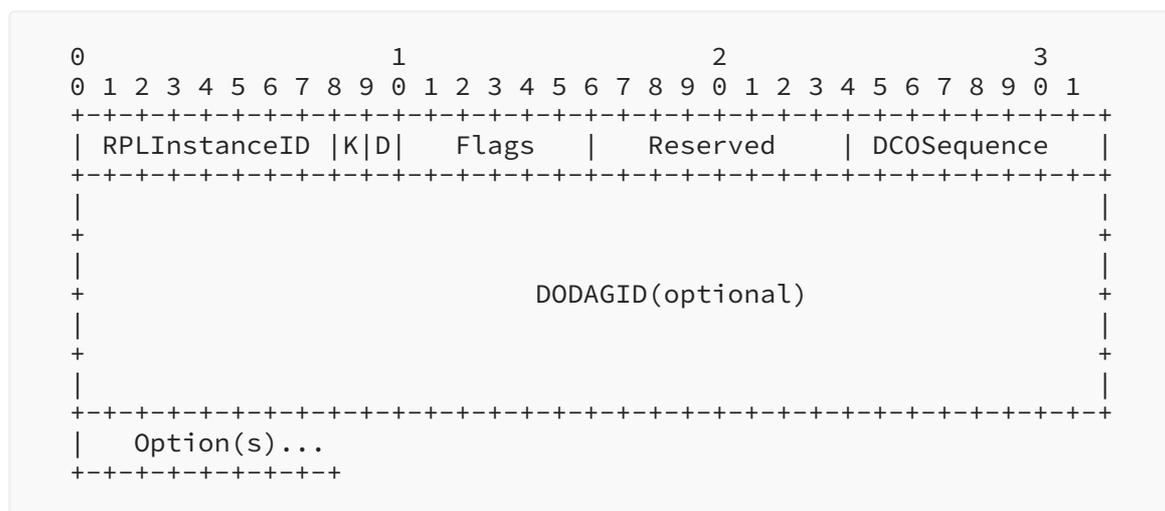


Figure 3: DCO base object

RPLInstanceID:

8-bit field indicating the topology instance associated with the DODAG, as learned from the DIO.

K:

The 'K' flag indicates that the recipient of DCO message is expected to send a DCO-ACK back. If the DCO-ACK is not received even after setting the 'K' flag, an implementation may retry the DCO at a later time. The number of retries are implementation and deployment dependent and are expected to be kept similar with those used in DAO retries in [\[RFC6550\]](#). [Section 4.6.3](#) specifies the considerations for DCO retry. A node receiving a DCO message without the 'K' flag set **MAY** respond with a DCO-ACK, especially to report an error condition. An example

error condition could be that the node sending the DCO-ACK does not find the routing entry for the indicated target. When the sender does not set the 'K' flag it is an indication that the sender does not expect a response, and the sender **SHOULD NOT** retry the DCO.

D:

The 'D' flag indicates that the DODAGID field is present. This flag **MUST** be set when a local RPLInstanceID is used.

Flags:

The 6 bits remaining unused in the Flags field are reserved for future use. These bits **MUST** be initialized to zero by the sender and **MUST** be ignored by the receiver.

Reserved:

8-bit unused field. The field **MUST** be initialized to zero by the sender and **MUST** be ignored by the receiver.

DCOSequence:

8-bit field incremented at each unique DCO message from a node and echoed in the DCO-ACK message. The initial DCOSequence can be chosen randomly by the node. [Section 4.4](#) explains the handling of the DCOSequence.

DODAGID (optional):

128-bit unsigned integer set by a DODAG root that uniquely identifies a DODAG. This field **MUST** be present when the 'D' flag is set and **MUST NOT** be present if 'D' flag is not set. DODAGID is used when a local RPLInstanceID is in use, in order to identify the DODAGID that is associated with the RPLInstanceID.

4.3.1. Secure DCO

A Secure DCO message follows the format in Figure 7 of [[RFC6550](#)], where the base message format is the DCO message shown in [Figure 3](#).

4.3.2. DCO Options

The DCO message **MUST** carry at least one RPL Target and the Transit Information Option and **MAY** carry other valid options. This specification allows for the DCO message to carry the following options:

0x00	Pad1
0x01	PadN

0x05	RPL Target
0x06	Transit Information
0x09	RPL Target Descriptor

Table 1

Section 6.7 of [RFC6550]

4.3.3. Path Sequence number in the DCO

A DCO message may contain a Path Sequence in the Transit Information Option to identify the freshness of the DCO message. The Path Sequence in the DCO **MUST** use the same Path Sequence number present in the regular DAO message when the DCO is generated in response to a DAO message. Thus if a DCO is received by a 6LR and subsequently a DAO is received with an old sequence number, then the DAO **MUST** be ignored. When the DCO is generated in response to a DCO from upstream parent, the Path Sequence **MUST** be copied from the received DCO.

4.3.4. Destination Cleanup Option Acknowledgment (DCO-ACK)

The DCO-ACK message **SHOULD** be sent as a unicast packet by a DCO recipient in response to a unicast DCO message with 'K' flag set. If 'K' flag is not set then the receiver of the DCO message **MAY** send a DCO-ACK, especially to report an error condition.

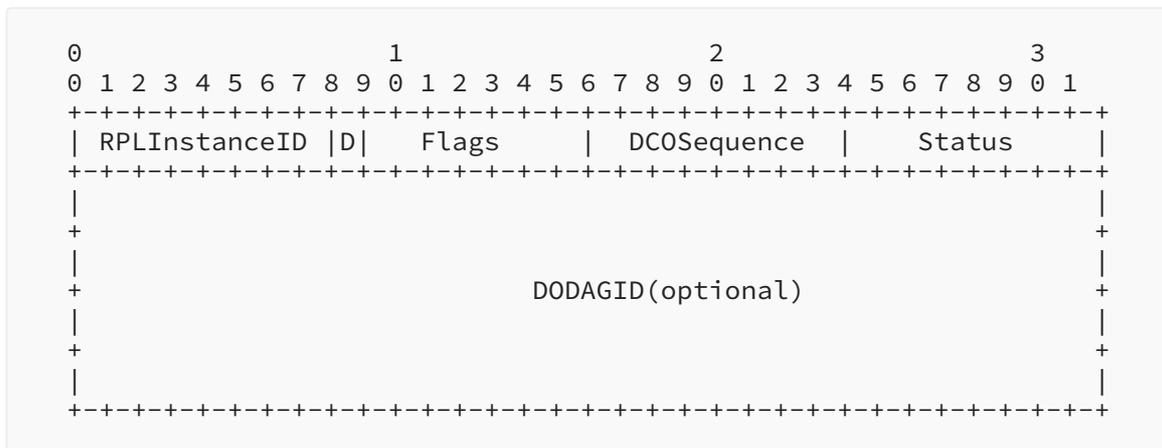


Figure 4: DCO-ACK base object

RPLInstanceID:

8-bit field indicating the topology instance associated with the DODAG, as learned from the DIO.

RPLInstanceID:

8-bit field indicating the topology instance associated with the DODAG, as learned from the DIO.

D:

The 'D' flag indicates that the DODAGID field is present. This flag **MUST** be set when a local RPLInstanceID is used.

Flags:

7-bit unused field. The field **MUST** be initialized to zero by the sender and **MUST** be ignored by the receiver.

DCOSequence:

8-bit field. The DCOSequence in DCO-ACK is copied from the DCOSequence received in the DCO message.

Status:

Indicates the completion. Status 0 is defined as unqualified acceptance in this specification. Status 1 is defined as "No routing-entry for the Target found". The remaining status values are reserved as rejection codes.

DODAGID (optional):

128-bit unsigned integer set by a DODAG root that uniquely identifies a DODAG. This field **MUST** be present when the 'D' flag is set and **MUST NOT** be present when 'D' flag is not set. DODAGID is used when a local RPLInstanceID is in use, in order to identify the DODAGID that is associated with the RPLInstanceID.

4.3.5. Secure DCO-ACK

A Secure DCO-ACK message follows the format in Figure 7 of [RFC6550], where the base message format is the DCO-ACK message shown in Figure 4.

4.4. DCO Base Rules

1. If a node sends a DCO message with newer or different information than the prior DCO message transmission, it **MUST** increment the DCOSequence field by at least one. A DCO message transmission that is identical to the prior DCO message transmission **MAY** increment the

DCOSequence field. The DCOSequence counter follows the sequence counter operation as defined in [Section 7.2](#) of [\[RFC6550\]](#)

2. The RPLInstanceID and DODAGID fields of a DCO message **MUST** be the same value as that of the DAO message in response to which the DCO is generated on the common ancestor node.
3. A node **MAY** set the 'K' flag in a unicast DCO message to solicit a unicast DCO-ACK in response in order to confirm the attempt.
4. A node receiving a unicast DCO message with the 'K' flag set **SHOULD** respond with a DCO-ACK. A node receiving a DCO message without the 'K' flag set **MAY** respond with a DCO-ACK, especially to report an error condition.
5. A node receiving a unicast DCO message **MUST** verify the stored Path Sequence in context to the given target. If the stored Path Sequence is more fresh, newer than the Path Sequence received in the DCO, then the DCO **MUST** be dropped.
6. A node that sets the 'K' flag in a unicast DCO message but does not receive DCO-ACK in response **MAY** reschedule the DCO message transmission for another attempt, up until an implementation specific number of retries.
7. A node receiving a unicast DCO message with its own address in the RPL Target Option **MUST** strip-off that Target Option. If this Target Option is the only one in the DCO message then the DCO message **MUST** be dropped.

The scope of DCOSequence values is unique to the node which generates it.

4.5. Unsolicited DCO

A 6LR may generate an unsolicited DCO to unilaterally cleanup the path on behalf of the target entry. The 6LR has all the state information, namely, the Target address and the Path Sequence, required for generating DCO in its routing table. The conditions why 6LR may generate an unsolicited DCO are beyond the scope of this document but some possible reasons could be:

1. On route expiry of an entry, a 6LR may decide to graciously cleanup the entry by initiating DCO.
2. 6LR needs to entertain higher priority entries in case the routing table is full, thus resulting in eviction of an existing routing entry. In this case the eviction can be handled graciously using DCO.

Note that if the 6LR initiates a unilateral path cleanup using DCO and if it has the latest state for the target then the DCO would finally reach the target node. Thus the target node would be informed of its invalidation.

4.6. Other considerations

4.6.1. Dependent Nodes invalidation

Current RPL [RFC6550] does not provide a mechanism for route invalidation for dependent nodes. This document allows the dependent nodes invalidation. Dependent nodes will generate their respective DAOs to update their paths, and the previous route invalidation for those nodes should work in the similar manner described for switching node. The dependent node may set the I-flag in the Transit Information Option as part of regular DAO so as to request invalidation of previous route from the common ancestor node.

Dependent nodes do not have any indication regarding if any of their parents in turn have decided to switch their parent. Thus for route invalidation the dependent nodes may choose to always set the 'I' flag in all its DAO message's Transit Information Option. Note that setting the I-flag is not counterproductive even if there is no previous route to be invalidated.

4.6.2. NPDAO and DCO in the same network

The current NPDAO mechanism in [RFC6550] can still be used in the same network where DCO is used. The NPDAO messaging can be used, for example, on route lifetime expiry of the target or when the node simply decides to gracefully terminate the RPL session on graceful node shutdown. Moreover, a deployment can have a mix of nodes supporting the DCO and the existing NPDAO mechanism. It is also possible that the same node supports both the NPDAO and DCO signaling for route invalidation.

Section 9.8 of [RFC6550] **SHOULD** send a No-Path DAO message to that removed DAO parent to invalidate the existing router". This document introduces an alternative and more optimized way of route invalidation but it also allows existing NPDAO messaging to work. Thus an implementation has two choices to make when a route invalidation is to be initiated:

1. Use NPDAO to invalidate the previous route and send regular DAO on the new path.
2. Send regular DAO on the new path with the 'I' flag set in the Transit Information Option such that the common ancestor node initiates the DCO message downstream to invalidate the previous route.

This document recommends using option 2 for reasons specified in Section 3 in this document.

This document assumes that all the 6LRs in the network support this specification. If there are 6LRs en-route DCO message path which do not support this document, then the route invalidation for corresponding targets may not work or may work partially i.e., only part of the path supporting DCO

may be invalidated. Alternatively, a node could generate an NPDAO if it does not receive a DCO with itself as target within specified time limit. The specified time limit is deployment specific and depends upon the maximum depth of the network and per hop average latency. Note that sending NPDAO and DCO for the same operation would not result in unwanted side-effects because the acceptability of NPDAO or DCO depends upon the Path Sequence freshness.

4.6.3. Considerations for DCO retry

A DCO message could be retried by a sender if it sets the 'K' flag and does not receive a DCO-ACK. The DCO retry time could be dependent on the maximum depth of the network and average per hop latency. This could range from 2 seconds to 120 seconds depending on the deployment. In case the latency limits are not known, an implementation **MUST NOT** retry more than once in 3 seconds and **MUST NOT** retry more than 3 times.

The number of retries could also be set depending on how critical the route invalidation could be for the deployment and the link layer retry configuration. For networks supporting only MP2P and P2MP flows, such as in AMI and telemetry applications, the 6LRs may not be very keen to invalidate routes, unless they are highly memory-constrained. For home and building automation networks which may have substantial P2P traffic, the 6LRs might be keen to invalidate efficiently because it may additionally impact the forwarding efficiency.

4.6.4. DCO with multiple preferred parents

[RFC6550] allows a node to select multiple preferred parents for route establishment. [Section 9.2.1 of \[RFC6550\]](#) **MUST** be sent with the same Path Sequence in the Transit Information". Subsequently when route invalidation has to be initiated, RPL mentions use of NPDAO which can be initiated with an updated Path Sequence to all the parent nodes through which the route is to be invalidated.

With DCO, the Target node itself does not initiate the route invalidation and it is left to the common ancestor node. A common ancestor node when it discovers an updated DAO from a new next-hop, it initiates a DCO. With multiple preferred parents, this handling does not change. But in this case it is recommended that an implementation initiates a DCO after a time period (DelayDCO) such that the common ancestor node may receive updated DAOs from all possible next-hops. This will help to reduce DCO control overhead i.e., the common ancestor can wait for updated DAOs from all possible directions before initiating a DCO for route invalidation. After timeout, the DCO needs to be generated for all the next-hops for whom the route invalidation needs to be done.

This document recommends using a DelayDCO timer value of 1sec. This value is inspired by the default DelayDAO value of 1sec in [RFC6550]. Here the hypothesis is that the DAOs from all possible parent sets would be received on the common ancestor within this time period.

It is still possible that a DCO is generated before all the updated DAOs from all the paths are received. In this case, the ancestor node would start the invalidation procedure for paths from which the updated DAO is not received. The DCO generated in this case would start invalidating the segments along these paths on which the updated DAOs are not received. But once the DAO reaches these segments, the routing state would be updated along these segments and should not lead to any inconsistent routing state.

Note that there is no requirement for synchronization between DCO and DAOs. The DelayDCO timer simply ensures that the DCO control overhead can be reduced and is only needed when the network contains nodes using multiple preferred parent.

5. Acknowledgments

Many thanks to Alvaro Retana, Cenk Gundogan, Simon Duquennoy, Georgios Papadopoulos, Peter Van Der Stok for their review and comments. Alvaro Retana helped shape this document's final version with critical review comments.

6. IANA Considerations

IANA is requested to allocate new codes for the DCO and DCO-ACK messages from the RPL Control Codes registry.

Code	Description	Reference
TBD1	Destination Cleanup Object	This document
TBD2	Destination Cleanup Object Acknowledgment	This document
TBD3	Secure Destination Cleanup Object	This document
TBD4	Secure Destination Cleanup Object Acknowledgment	This document

Table 2

IANA is requested to allocate bit 1 from the Transit Information Option Flags registry for the I-flag ([Section 4.2](#))

6.1. New Registry for the Destination Cleanup Object (DCO) Flags

IANA is requested to create a registry for the 8-bit Destination Cleanup Object (DCO) Flags field. This registry should be located in existing category of "Routing Protocol for Low Power and Lossy Networks (RPL)".

New bit numbers may be allocated only by an IETF Review. Each bit is tracked with the following qualities:

- Bit number (counting from bit 0 as the most significant bit)
- Capability description
- Defining RFC

The following bits are currently defined:

Bit number	Description	Reference
0	DCO-ACK request (K)	This document
1	DODAGID field is present (D)	This document

Table 3: DCO Base Flags

6.2. New Registry for the Destination Cleanup Object Acknowledgment (DCO-ACK) Status field

IANA is requested to create a registry for the 8-bit Destination Cleanup Object Acknowledgment (DCO-ACK) Status field. This registry should be located in existing category of "Routing Protocol for Low Power and Lossy Networks (RPL)".

New Status values may be allocated only by an IETF Review. Each value is tracked with the following qualities:

- Status Code
- Description
- Defining RFC

The following values are currently defined:

Status Code	Description	Reference
0	Unqualified acceptance	This document
1	No routing-entry for the indicated Target found	This document

Table 4: DCO-ACK Status Codes

6.3. New Registry for the Destination Cleanup Object (DCO) Acknowledgment Flags

IANA is requested to create a registry for the 8-bit Destination Cleanup Object (DCO) Acknowledgment Flags field. This registry should be located in existing category of "Routing Protocol for Low Power and Lossy Networks (RPL)".

New bit numbers may be allocated only by an IETF Review. Each bit is tracked with the following qualities:

- Bit number (counting from bit 0 as the most significant bit)
- Capability description
- Defining RFC

The following bits are currently defined:

Bit number	Description	Reference
0	DODAGID field is present (D)	This document

Table 5: DCO-ACK Base Flags

7. Security Considerations

This document introduces the ability for a common ancestor node to invalidate a route on behalf of the target node. The common ancestor node could be directed to do so by the target node using the I-flag in DCO's Transit Information Option. However, the common ancestor node is in a position to unilaterally initiate the route invalidation since it possesses all the required state information, namely, the Target address and the corresponding Path Sequence. Thus a rogue common ancestor node could initiate such an invalidation and impact the traffic to the target node.

This document also introduces an I-flag which is set by the target node and used by the ancestor node to initiate a DCO if the ancestor sees an update in the route adjacency. However, this flag could be spoofed by a malicious 6LR in the path and can cause invalidation of an existing active path. Note that invalidation will happen only if the other conditions such as Path Sequence condition is also met. Having said that, such a malicious 6LR may spoof a DAO on behalf of the (sub) child with the I-flag set and can cause route invalidation on behalf of the (sub) child node. Note that, using existing mechanisms offered by [RFC6550], a malicious 6LR might also spoof a DAO with lifetime of zero or otherwise cause denial of service by dropping traffic entirely, so the new mechanism described in this document does not present a substantially increased risk of disruption.

This document assumes that the security mechanisms as defined in [RFC6550] are followed, which means that the common ancestor node and all the 6LRs are part of the RPL network because they have the required credentials. A non-secure RPL network needs to take into consideration the risks highlighted in this section as well as those highlighted in [RFC6550].

All RPL messages support a secure version of messages which allows integrity protection using either a MAC or a signature. Optionally, secured RPL messages also have encryption protection for confidentiality.

The document adds new messages (DCO, DCO-ACK) which are syntactically similar to existing RPL messages such as DAO, DAO-ACK. Secure versions of DCO and DCO-ACK are added similar to other RPL messages (such as DAO, DAO-ACK).

RPL supports three security modes as mentioned in Section 10.1 of [RFC6550]

1. Unsecured: In this mode, it is expected that the RPL control messages are secured by other security mechanisms, such as link-layer security. In this mode, the RPL control messages, including DCO, DCO-ACK, do not have Security sections. Also note that unsecured mode does not imply that all messages are sent without any protection.
2. Preinstalled: In this mode, RPL uses secure messages. Thus secure versions of DCO, DCO-ACK **MUST** be used in this mode.
3. Authenticated: In this mode, RPL uses secure messages. Thus secure versions of DCO, DCO-ACK **MUST** be used in this mode.

8. 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>>.

Appendix A. Example Messaging

A.1. Example DCO Messaging

In [Figure 1](#), node (D) switches its parent from (B) to (C). This example assumes that Node D has already established its own route via Node B-G-A-6LBR using pathseq=x. The example uses DAO and DCO messaging convention and specifies only the required parameters to explain the example namely, the parameter 'tgt', which stands for Target Option and value of this parameter specifies the address of the target node. The parameter 'pathseq', which specifies the Path Sequence value carried in the Transit Information Option. The parameter 'I_flag' specifies the 'I' flag in the Transit Information Option. sequence of actions is as follows:

1. Node D switches its parent from node B to node C
2. D sends a regular DAO(tgt=D,pathseq=x+1,I_flag=1) in the updated path to C
3. C checks for a routing entry on behalf of D, since it cannot find an entry on behalf of D it creates a new routing entry and forwards the reachability information of the target D to H in a DAO (tgt=D,pathseq=x+1,I_flag=1).
4. Similar to C, node H checks for a routing entry on behalf of D, cannot find an entry and hence creates a new routing entry and forwards the reachability information of the target D to A in a DAO(tgt=D,pathseq=x+1,I_flag=1).
5. Node A receives the DAO(tgt=D,pathseq=x+1,I_flag=1), and checks for a routing entry on behalf of D. It finds a routing entry but checks that the next hop for target D is different (i.e., Node G). Node A checks the I_flag and generates DCO(tgt=D,pathseq=x+1) to previous next hop for target

- D which is G. Subsequently, Node A updates the routing entry and forwards the reachability information of target D upstream DAO($\text{tgt}=\text{D}, \text{pathseq}=\text{x}+1, \text{I_flag}=1$).
6. Node G receives the DCO($\text{tgt}=\text{D}, \text{pathseq}=\text{x}+1$). It checks if the received path sequence is later than the stored path sequence. If it is later, Node G invalidates the routing entry of target D and forwards the (un)reachability information downstream to B in DCO($\text{tgt}=\text{D}, \text{pathseq}=\text{x}+1$).
 7. Similarly, B processes the DCO($\text{tgt}=\text{D}, \text{pathseq}=\text{x}+1$) by invalidating the routing entry of target D and forwards the (un)reachability information downstream to D.
 8. D ignores the DCO($\text{tgt}=\text{D}, \text{pathseq}=\text{x}+1$) since the target is itself.
 9. The propagation of the DCO will stop at any node where the node does not have an routing information associated with the target. If cached routing information is present and the cached Path Sequence is higher than the value in the DCO, then the DCO is dropped.

A.2. Example DCO Messaging with multiple preferred parents

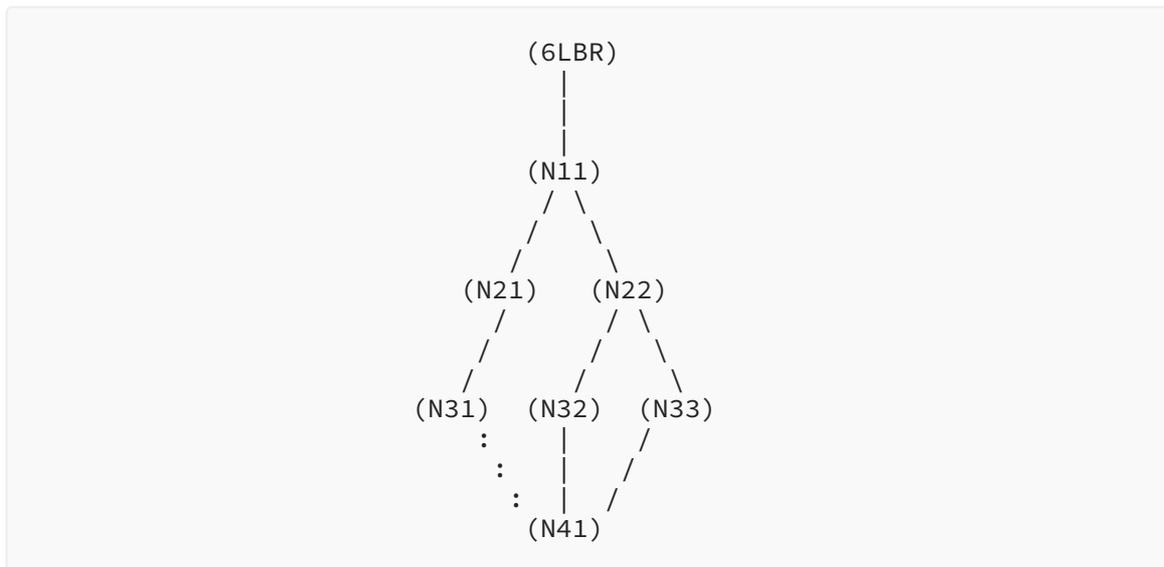


Figure 5: Sample topology 2

In [Figure 5](#), node (N41) selects multiple preferred parents (N32) and (N33). The sequence of actions is as follows:

1. (N41) sends DAO($\text{tgt}=\text{N41}, \text{PS}=\text{x}, \text{I_flag}=1$) to (N32) and (N33). Here I_flag refers to the Invalidation flag and PS refers to Path Sequence in Transit Information option.

2. (N32) sends DAO(tgt=N41,PS=x,I_flag=1) to (N22). (N33) also sends DAO (tgt=N41,PS=x,I_flag=1) to (N22). (N22) learns multiple routes for the same destination (N41) through multiple next-hops. (N22) may receive the DAOs from (N32) and (N33) in any order with the I_flag set. The implementation should use the DelayDCO timer to wait to initiate the DCO. If (N22) receives an updated DAO from all the paths then the DCO need not be initiated in this case. Thus the route table at N22 should contain (Dst,NextHop,PS): { (N41,N32,x), (N41,N33,x) }.
3. (N22) sends DAO(tgt=N41,PS=x,I_flag=1) to (N11).
4. (N11) sends DAO(tgt=N41,PS=x,I_flag=1) to (6LBR). Thus the complete path is established.
5. (N41) decides to change preferred parent set from { N32, N33 } to { N31, N32 }.
6. (N41) sends DAO(tgt=N41,PS=x+1,I_flag=1) to (N32). (N41) sends DAO(tgt=N41,PS=x+1,I_flag=1) to (N31).
7. (N32) sends DAO(tgt=N41,PS=x+1,I_flag=1) to (N22). (N22) has multiple routes to destination (N41). It sees that a new Path Sequence for Target=N41 is received and thus it waits for pre-determined time period (DelayDCO time period) to invalidate another route {(N41),(N33),x}. After time period, (N22) sends DCO(tgt=N41,PS=x+1) to (N33). Also (N22) sends the regular DAO(tgt=N41,PS=x+1,I_flag=1) to (N11).
8. (N33) receives DCO(tgt=N41,PS=x+1). The received Path Sequence is latest and thus it invalidates the entry associated with target (N41). (N33) then sends the DCO(tgt=N41,PS=x+1) to (N41). (N41) sees itself as the target and drops the DCO.
9. From Step 6 above, (N31) receives the DAO(tgt=N41,PS=x+1,I_flag=1). It creates a routing entry and sends the DAO(tgt=N41,PS=x+1,I_flag=1) to (N21). Similarly (N21) receives the DAO and subsequently sends the DAO(tgt=N41,PS=x+1,I_flag=1) to (N11).
10. (N11) receives DAO(tgt=N41,PS=x+1,I_flag=1) from (N21). It waits for DelayDCO timer since it has multiple routes to (N41). (N41) will receive DAO(tgt=N41,PS=x+1,I_flag=1) from (N22) from Step 7 above. Thus (N11) has received regular DAO(tgt=N41,PS=x+1,I_flag=1) from all paths and thus does not initiate DCO.
11. (N11) forwards the DAO(tgt=N41,PS=x+1,I_flag=1) to 6LBR and the full path is established.

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