ROLL Working Group
Internet-Draft
Intended status: Standards Track
Expires: October 2, 2009

P. Thubert
Cisco
T. Watteyne
UC Berkeley
Z. Shelby
Sensinode
D. Barthel
Orange Labs

March 31, 2009

# LLN Routing Fundamentals
# draft-thubert-roll-fundamentals-00

## Status of this Memo



## Copyright Notice

Abstract

This document describes a basic set of fundamental mechanisms for routing on a Low-power and Lossy Network (LLN). It does not intend to specify a full-blown protocol. It is rather offered as a basis to support the discussion while designing the ROLL protocol.

Table of Contents

## 1. Introduction

This document describes a basic set of fundamental mechanisms for routing on a Low-power and Lossy Network (LLN) appropriate for scenarios identified by the ROLL working group. It does not intend to specify a full-blown protocol. It is rather offered as a basis to support the discussion while designing the ROLL protocol. The fundamental mechanisms proposed stem from our analysis that current academic, industrial and IETF protocols suitable to ROLL scenarios are reduceable to those basic mechanisms.

Those mechanisms provide a core set of functionality that can be complemented by specific extensions to implement the needs expressed in the ROLL routing requirement drafts:

- Urban WSNs Routing Requirements in Low Power and Lossy Networks [I-D.ietf-roll-urban-routing-reqs]

- Building Automation Routing Requirements in Low Power and Lossy Networks [I-D.ietf-roll-building-routing-reqs]

- Home Automation Routing Requirements in Low Power and Lossy Networks [I-D.ietf-roll-home-routing-reqs]

- Industrial Routing Requirements in Low Power and Lossy Networks [I-D.ietf-roll-indus-routing-reqs]

The constraints expressed in the routing requirement documents (such as on node memory and communication cost) narrow the choice of

fundamental mechanisms down to very simple ones.

Due to the highly directed flows in LLNs, a tree structure comes naturally to mind as a bare minimum. In a slightly more elaborate mechanism, we propose that each router memorizes a few best neighbor routers (not only among its parents up the tree, but also among its siblings), to choose from (using some routing metric) when routing towards LLN Border Routers (LBR). However, to reduce complexity, we propose that only the best parent be used for routing advertisements up the structure towards the LBRs, giving each of them a simple tree representation to be used to route downstream traffic or to make other global decisions. Since links and nodes are expected to come and go over time, mechanisms for tree reorganization are described. However, on a shorter time scale, transient link failures are bound to happen. In such a case, we recommend that the link-layer passes packets back to the network layer for re-routing along alternate paths.

In terms of routing, the basic fundamental methods include uni/





anycast routing up the graph and unicast routing down the tree (either hop-by-hop or source-based). The best neighbor selection mechanism is left to the protocol design phase. We even suggest that it be left as a plug-in for future evolution. However, a set of basic tree discovery and forwarding rules, described here, prevents loops from forming, in most cases, whatever the routing algorithm eventually implemented.

More advanced mechanisms which can be built upon the fundamental mechanisms are also described. They include route optimizations, dissemination of a digraph, dissemination and maintenance of multiple overlapping trees, prefix aggregation and advanced forwarding rules.

This document is organized as follows:

Section 1.1 defines the terminology used in this document.

Section 2 concentrates on the basic tree discovery and maintenance mechanism.

Section 3 introduces the basic distance-vector route dissemination mechanism.

Section 4 describes the upstream and downstream forwarding rules.

Section 5 describes multicast support.

Section 6 describes advanced mechanisms which can be built upon these fundamentals.

## 1.1. Terminology

The terminology used in this document is consistent with and incorporates that described in [I-D.ietf-roll-terminology]. This terminology is extended in this document as follows:

Discovery: a mechanism by which a logical representation of the network is built.

Router: a network node that is capable of forwarding packets on behalf of other nodes. In ROLL routing requirement documents, it appears that most nodes are expected to be routers.

Default Router: the router to turn to when a node has no information on where to forward a packet





Route Dissemination: the action of establishing state within the network so that routers know how to route packets related to some source-destination pairs.

Graph: a set of vertices and edges to represent a network of nodes and links. A Directed Acyclic Graph (DAG) is a graph with directional edges where no loop is formed.

Tree: a simple form of graph in which there is only one possible route from any node to a specific node called the root. An LLN is said to be Grounded if it is connected to a high-capacity backbone or link to a network such as the Internet. By contrast, an LLN is said to be Floating if it is not grounded.

Tree Depth: the maximum number of edges that need to be traversed

from any tree node to the root.

Uniform Path Metric: A scalar measure for the quality of the bi-directional path between the LLN Router and the root.

## 1.2. Needs

The ROLL working group has identified typical scenarios and their related requirements for LLN routing. The main requirements on any fundamental mechanisms used for achieving the ROLL protocol can be summarized as follows:

- Support for operation in both full IPv6 [RFC2460] and minimal 6LoWPAN [RFC4944] networks.
- Optimized for traffic directed between nodes and LBRs.
- The use of multiple default routers whenever possible.
- Support for multiple LBRs out of the LLN.
- Minimal network state needed by routers, with a hard bound better than O(D).
- Support for complex unicast, anycast and multicast flows.
- Localized response upon link failures without requiring global updates.
- Minimal control overhead scaling within O(log(L)) of the data rate.





- Support for link and node costs along routes.

# 2. Tree Discovery

A tree is the simplest and most basic acyclic graph structure. Even if it is not sufficient to ensure by itself the multipath forwarding proposed below, a tree provides the ideal structure for best path

routing between source and sink in a convergecast.

In many occasions, LLNs do not have a clear and stable physical structure and it becomes necessary to overlay a logical representation to define links and enable IPv6 operations. LLN Tree Discovery is the component of the LLN fundamentals that builds and maintains logical tree structures over the LLN.

The nodes in the LLN discovery tree are Routers; the root is an arbitrary elected Router if the network is isolated; it is the LLN Border Router (LBR) if the LLN is connected to the infrastructure via a backhaul link. A federating backbone such as an extended LoWPAN backbone is the virtual root of the federated tree. In that case, the LBRs are attached at a depth of one and are in charge of performing the root operations on behalf of that virtual root.

A tree is identified by a Tree ID which can take the form of an IPv6 address: in the case of a LoWPAN configuration with a backbone, the LoWPAN prefix is used as the Tree ID. In the case of an isolated network, that will be an address of the root.

This section describes

1. a minimum extension to IPv6 Neighbor Discovery Router Advertisements in order to ensure that LLN Routers organize in a tree structure, and

2. a minimum common algorithmic part that all LLN Routers are required to implement in order to ensure that, whatever their individual routing decisions, routing loops between LLN Routers are avoided and a basic optimization is achieved.

LLN Discovery is based on an autonomous decision by each Router with no global state convergence such as traditionally found in IGPs. In order to enable backward compatibility and interoperability, LLN Discovery allows Routers to make different decisions from identical inputs, based on their own configuration and their own algorithms, though it is highly preferable that the decision algorithm be consistent in a given deployment to achieve the specific goals of that deployment.





The signalling mechanism that is used to form the trees is an

extension to the ICMP Router Advertisement (RA) message, namely the Tree Information Option (TIO). The TIO allows LLN Routers to advertise the tree they belong to, and to select and move to the best location within the available trees. LLN Routers propagate the TIO in RA messages down the tree, updating some metrics such as the Tree Depth, leaving other information such as the Tree ID unchanged, and resending the result in its own RAs. This is compatible with RA period reduction techniques such as the use of Trickle.

## 2.1. Overview

LLN Tree Discovery is a form of distance vector protocol for use in wireless meshed networks. Tree Discovery locates the nearest exit and forms Directed Graphs towards that exit, composed of a best path tree and alternate forwarding options.

By introducing the concept of routing plug-ins, LLN Tree Discovery enables LLN Routers to implement different policies for selecting their preferred parent in the Tree. Tree Discovery does not specify the plug-in operation, but rather specifies a set of rules to be implemented by all plug-ins to ensure interoperability.

The Tree Depth is the underlying criterion that garantees loop-free operations even if plug-ins implement different policies, and even if these policies do not use Depth as a routing metric.

In order to organize and maintain a loopfree structure, the parent selection plug-ins in the LLN Routers MUST obey the following rules and definitions:

1. An LLN Router that is not attached to a parent Router is the root of its own floating tree. Its depth is zero. An LLN Router that looses its current parent and has no alternate parent that it can attach to also adopts a depth of zero, but remembers the Tree ID and the sequence counter in the TIO of the lost parent for a period of time which covers multiple TIOs.

2. An LLN Border Router that is attached to a federating backbone acts as root and advertises a depth of one. An LBR that is not attached to a federating backbone is a root and exposes a depth of zero.

3. A router sending an RA without TIO is considered a grounded parent Router at depth 0.

4. The root of a tree exposes the tree in the Router Advertisement (RA) Tree Information Option (TIO) and LLN Routers propagate the

TIO down.

5. An LLN Router that is already part of a tree MAY move at any time and with no delay in order to get closer to the root of its current tree, i.e. in order to reduce its own tree depth. But an LLN Router MUST NOT move down the tree that it is attached to. LLN Routers MUST ignore RAs that are received from other routers located deeper within the same tree.

6. A LLN Router may move from its current tree into any different tree at any time and whatever the depth it reaches in the new tree but, before it can do so, it may have to wait for a Tree Hop Timer to elapse. If the router was root of its own floating tree, it may join its previous tree (identified by the last parent Tree ID) only if the sequence number in the TIO was incrememented since the LLN Router left that tree, indicating that the candidate parent was not attached behind this LLN Router and kept getting subsequent TIOs from the same tree. The LLN Router will join that other tree if it is preferable for reasons of connectivity, configured preference, free medium time, size, security, bandwidth, tree depth, or whatever metrics the LLN Router cares to use.

7. If an LLN Router has selected a new parent router but has not moved yet (because it is waiting for Tree Hop Timer to elapse), the LLN Router is said to be unstable and it refrains from sending Router Advertisement - Tree Information Options.

8. When a LLN Router joins a tree, it moves within its own tree or receives a modified TIO from its current parent router, the LLN Router sends out an unsolicited Router Advertisement message with TIO that propagates the new tree information.

9. This allows the new higher parts of the tree to be updated first, eventually dragging their sub-tree with them, and allowing stepped sub-tree reconfigurations, limiting relative movements.

## 2.2. Discovery Information

The Tree Information Option carries a number of metrics and other information that allows an LLN Router to discover a tree and select its parent while avoiding loop generation.

TIO Base option

The Tree Information Option is a container option, which might contain a number of suboptions. The base option regroups the minimum information set that is mandatory to operate the LLN Discovery Algorithm.

Grounded (G): The Grounded (G) flag is set when the tree is attached to a fixed network infrastructure (such as the Internet).

Sequence Number: An integer that is incremented by the root for each TIO sent on a link. It is propagated unchanged down the tree.

Boot Time Random: A random number used to resolve collisions. Its value is computed at boot time and recomputed in case of a collision. Each LLN Router in the propagation chain sets this TIO field to its own value.

Tree Depth: If the root is attached to a federating backbone, its Tree Depth is 1, otherwise it is 0. The Tree Depth of an LLN Router is the depth of its parent as received in a TIO, incremented by at least one. All the nodes in the tree advertise their Tree Depth in the Tree Information Options that they append to the RA messages as part of the propagation process.

Tree Delay: An unsigned integer set by the root indicating the delay before changing the tree configuration. It is expected to be at least an order of magnitude shorter than the RA interval and at least an order of magnitude larger than the typical propagation delay inside the LLN.

Path Digest: An unsigned integer CRC, updated by each Router. This is the result of a computation on a bit string obtained by appending the received value and the Router address used to attach to his parent. LBRs use a 'previous value' of zeroes to initially set the Path Digest.

Tree ID: An unsigned integer which uniquely identifies a tree.

This value is set by the root to one of its ULA or global addresses or prefixes.

Uniform Path Metric: A scalar measure for the quality of the bi-directional path between the LLN Router and the root.





The following values MUST not change during the propagation of the TIO down the tree: G, Tree Delay and Tree ID. All other fields are updated at each hop of the propagation.

In addition to the minimum set of information required, a number of options can are used, e.g. for bandwidth, stability, preference etc.

## 2.3. Tree Selection

The tree selection is implementation and algorithm dependent. In order to limit erratic movements, and all metrics being equal, LLN Routers SHOULD stick to their previous selection. Also, LLN Routers SHOULD provide a means to filter out candidate parent Routers whose availability is detected as fluctuating, at least when more stable choices are available. For instance, the LLN Router MAY place the failed parent Router in a Hold Down mode that prevents the parent Router from being reused for a given period of time.

The known trees are associated with the parent Router that advertises them and kept in a list by extending the Default Router List. DRL entries are extended to store the information received from the last TIO. These entries are managed by states and timers described in the next section.

When LLN connection to a fixed network is either not possible or not recommended, for security or other reasons, scattered trees should as much as possible be aggregated into larger trees in order to allow inner connectivity. How to balance these trees is implementation dependent, and MAY use a specific visitor-counter suboption in the TIO.

An LLN Router SHOULD verify that bidirectional connectivity is available with a candidate parent Router before it attaches to that candidate. Some link-layers such as 802.11 infrastructure mode will provide for this, while others such as 802.15.4 will not. If the link-layer does not guarantee bidirectional connectivity, then the LLN Router needs to make sure that it can reach the LBR. This is achieved using Neighbor Solicitation and refraining from attaching to an LBR for which no neighbor cache exists, or the state is still INCOMPLETE.

## 2.4. States

Parent routers in the DRL may or may not be usable for attachment depending on runtime conditions. The following states are defined:





Current This parent Router is currently used for attachment

Candidate This parent Router can be used for attachment.

Held-Up This parent Router can not be used till Tree Hop Timer elapses.

Held-Down This parent Router can not be used till Hold Down Timer elapses. At the end of the hold-down period, the router is removed from the DRL. It will be reinserted if it appears again in an RA.

Collision This parent Router can not be used until it transmits its next RA.

## 2.5. Stability

An LLN Router is instable when it is prepared to move shortly to another parent Router. This happens typically when the LLN Router has selected a more preferred candidate parent Router and has to wait for the Tree Hop Timer to elapse before roaming. Instability may also occur when the current parent Router is lost and the next best is still held up. Instability is resolved when the Tree Hop Timer of all the parent Router(s) causing instability elapse. Such parent Router is changes state to Current or Held- Down.

Instability is transient (on the order of Tree Hop Timers). When an LLN Router is unstable, it MUST NOT send RAs with TIO. This avoids loops when LLN Router A wishes to attach to LLN Router B and LLN Router B wishes to attach to LLN Router A. Unless RAs crisscross, a LLN Router receives TIO from stable parent Routers, which do not plan to attach to it, so the LLN Router can safely attach to them.

# 3. Route Dissemination

## 3.1. Overview

Route Dissemination is the second component of the LLN fundamental mechanisms. As explained previously, the first component, LLN Tree Discovery, establishes a logical tree structure over the LLN and sets up default routes towards the root. To establish the routing states towards the nodes in the LLN and enable complete reachability along the tree, it suffices for Route Dissemination to advertise up the tree the host, prefix and multicast routes.

As a result, the Default Router for an LLN Router is its parent up in the tree (upstream); and the more specific routes are always oriented





down the tree (downstream).

LLN Tree Discovery does not only provide loop avoidance for the Route Dissemination protocol; LLN Tree Discovery also triggers Route Dissemination each time a topological change occurs. The loopfree structure must be restored before Route Dissemination can operate again and repaint the tree with prefixes, addresses and group membership.

Each logical tree that LLN Tree Discovery forms is considered a separate routing topology. If an LLN Router belongs to multiple of such topologies, then it is expected that both the Route Dissemination signaling and the data packets are flagged to follow the topology for which the packet was introduced in the network.

The ROLL Route Dissemination protocol design follows a hierarchical model where a whole structure that is reachable via a node of the tree is abstracted as located within that node for the upper level of

network abstraction, exposing only the list of reachable prefixes, hosts, and multicast group listeners as opposed to the topological information to get there.

This allows an extreme conciseness of the routing information, with no topological knowledge past the first hop. That conciseness enables some degree of movement within the nested structure; in particular, a movement within a subtree is not seen outside of that subtree, so most of the connectivity is maintained at all times while there might never be such a thing as a convergence.

The ROLL Route Dissemination protocol defines a new information vector called the Route Information Option (RIO) to disseminate atomic routing information towards the root of the tree. Due to a topological change, a RIO can be received from a sub-tree where the originating router was but is no more, until its parents realize it is gone and stop advertising. By construction of the tree, there can be a single child to reach a given unicast resource, so older unicast routes can be flushed right away if a more recent advertisement comes from a different child. Multicast routes can only be explicitely removed or timed out.

A parent maintains a state for each information it learns from Route Dissemination. Advertisements are sequenced and the last sequence number is kept. An out-of-sequence RIO must be disregarded. If the RIO information appears valid, it is forwarded to the parent's parent in the next burst, carried by a RIO, together with the parent's own information.





## 3.2. Disseminated Information

Route Dissemination extends RFC4861 and RFC4191 to allow a node to include a new Route Information Option in ND messages such as Neighbor Advertisements (NAs).

In order to track the freshness of an advertisement, the RIO includes a sequence counter that is incremented each time the advertisment is reissued.

A depth is also added for tracking purposes; the depth is incremented

at each hop as the RIO is propagated up the tree.

Receiving a Tree Discovery TIO from the parent triggers the sending of a delayed advertisement back, with the collection of all known information.

An NA is also sent to the new parent once it has been selected after a movement, or when the list of advertised information has changed.

Route Dissemination may advertise positive (prefix is present) or negative (removed) RIOs. A no-RIO is stimulated by the disappearance of a route below. This is discovered by timing out after a request (a Tree Discovery TIO) or by receiving a no-RIO. A no-RIO is a RIO with a RIO Lifetime of 0.

The RIO base option carries sequenced route information for unicast and multicast; it contains:

Resource type: Prefix, host, or multicast group

Prefix Length: Number of valid leading bits in the IPv6 Prefix.

RIO Lifetime: The length of time in seconds (relative to the time the packet is sent) that the prefix is valid for route determination. A value of all one bits (0xFFFFFFFF) represents infinity. A value of all zero bits (0x00000000) indicates a loss of reachability.

RIO Depth: Set to 0 by the router that owns the resource and issues the RIO. Incremented by all routers that propagate the RIO towards the root.

RIO Sequence: Incremented by the router that owns the resource for each new RIO for that prefix. Left unchanged by all routers that propagate the RIO. A lollipop mechanism is used to wrap from 0xFFFF directly to 10.





Prefix: Variable-length field containing a prefix, an IPv6 address or a multicast group id. The Prefix Length field contains the number of valid leading bits in the prefix in the former case. The bits in the prefix after the prefix length (if any) are

reserved and MUST be initialized to zero by the sender and ignored by the receiver.

## 3.3. LLN Router Operation

The LLN Router operation is autonomous, based on the information provided by the potential parents in sight. Each router selects a parent in a loopfree and case-optimized fashion, and installs a default route up the tree via the selected parent. The resulting tree may never be globally stable enough to be mapped in a global graph. So the adaptation to local movements must be rapid and localized.

Route Dissemination information can be redistributed in another routing protocol, e.g. MANET or IGP. But the MANET or the IGP route information SHOULD NOT be redistributed into Route Dissemination. This creates a hierarchy of routing protocols where Route Dissemination routes stand somewhere between connected and IGP routes. See Section Section 6.1 for more discussion on integration with other routing protocols.

As a result:

- LLN Discovery establishes a tree using extended Neighbor Discovery RS/RA flows.
- A routing algorithm exploits the tree to get optimally out of LLN (default route).
- Route Dissemination extends Neighbor Discovery in order to quickly establish hop-by-hop routes down the tree.
- Source Routing can be used to provide additional routes towards nodes in the LLN. When there is existing hop-by-hop state in routers, the source routing information can be compressed.

Route Dissemination maintains abstract lists of known information. An entry contains the following abstract information:

- The state of the entry: ELAPSED, PENDING, or CONFIRMED.
- A reference to the adjacency that was created for that prefix.

- A reference to the ND entry that was created for the advertiser Neighbor.
- The IPv6 address of the advertiser Neighbor.
- The logical equivalent of the full Route Dissemination information.
- A reference to the interface of the advertiser Neighbor.
- A 'reported' Boolean to keep track whether this prefix was reported already to the parent parent.
- A counter of retries to count how many TIOs were sent on the interface to the neighbor without reachability confirmation for the prefix.

Route Dissemination stores the entries in either one of 3 abstract lists; the Connected, the Reachable and the Unreachable lists. In practice all part of a route table.

The Connected list corresponds to the resources owned by the LLN Router.

As long as an router keeps receiving RIOs for a given information timely, its entry is listed in the Reachable list.

Once scheduled to be destroyed, an entry is moved to the Unreachable list if the router has a parent to which it sends RIOs, otherwise the entry is cleaned up right away. The entry is removed from the Unreachable list when the parent changes or when a no-RIO is sent to the parent indicating the loss of the prefix.

Route Dissemination requires 2 timers; the DelayNA timer and the DestroyTimer.

- The DelayNA timer is armed upon a stimulation to send a RIO (such as a TIO from the parent). When the timer is armed, all entries in the Reachable list as well as all entries for Connected list are set to not reported yet.
- The DelayNA timer has a duration that is DEF_NA_LATENCY divided by 2 with the tree depth.
- The DestroyTimer is armed when at least one entry has exhausted its retries, which means that a number of TIO were sent over the interface but that the entry was not confirmed with a RIO. When

the destroy timer elapses, for all exhausted entries, the





associated route is removed, and the entry is scheduled to be destroyed.

- The Destroy timer has a duration of min (MAX_DESTROY_INTERVAL, RA_INTERVAL).

RIO Processing

When ND sends a NA to the parent, Route Dissemination extends the message with RIO options for:

* All the entries that are not 'DELETED'.

* All the entries in the removed list as no-RIO.

* All the pentries in the advertised list that are not reported yet.The entries are then set to reported.

When ND receives a NA from a visitor over a given interface, RIOs are processed in a loop. For known information, the sequence counter in the RIO is checked against the last received and the update is used only if the sequence is newer. This filters out obsolete advertisements when a node has moved between 2 subtrees attached to a same node.

If an information is advertised as a no-RIO, the associated route is removed, and the entry is transferred to the removed list. Otherwise, the proper routing table is looked up:

* If a preferred route to that source from another protocol already exists, the RIO is ignored.

* If a new route can be created, a new entry is allocated to track it, as CONFIRMED, but not reported.

* If a Route Dissemination route existed already via the same Neighbor, it is CONFIRMED.

* If an older unicast route existed via a different Neighbor, this is equivalent to a no-RIO for the previous entry followed

by a new RIO for the new entry. So the old entry is scheduled to be destroyed, whereas the new one is installed.

Unicast Route Dissemination messages from child to parent





When sending Route Dissemination to its parent, a router includes the RIOs about not already reported entries in the Reachable and Connected lists, as well as no-RIOs for all the entries in the Unreachable list.

Depending on its policy, the receiving router SHOULD install a route for the resource in the RIO via the link local address of the source router and it SHOULD propagate the information, either as a RIO or by means of redistribution into a routing protocol.

The TIO from the root is used to synchronize the whole tree. Its period is expected to range from 500ms to hours, depending on the stability of the configuration and the bandwidth available.

When an router receives a TIO over an egress interface from the current parent parent, the DelayNA is armed to force a full update. The router also issues a propagated TIO over all its relevant interfaces, after a small jitter that aims at minimizing collisions of TIO messages over the radio as it is propagated down the tree.

The design choice behind this is NOT TO synchronize the parent and children databases, but instead to update them regularly to cover from the loss of packets. The rationale for that choice is movement. If the topology can be expected to change frequently, synchronization might be an excessive goal in terms of exchanges and protocol complexity. This results in a simple protocol with no real peering.

When the router sends a TIO over an interface, for all entries on that interface:

* If the entry is CONFIRMED, it goes PENDING with the retry count

set to 0.

* If the entry is PENDING, the retry count is incremented. If it reaches a maximum threshold, the entry goes ELAPSED If at least one entry is ELAPSED at the end of the process: if the Destroy timer is not running then it is armed with a jitter.

Since the DelayNA has a duration that decreases with the depth, it is expected to receive all RIOs from all children before the timer elapses and the full update is sent to the parent.

Other events





Finally, Route Dissemination listens to a series of events, such as:

* router stopped or unable to run: Route Dissemination routes are cleaned up. Route Dissemination is inactive.

* Route Dissemination operation stopped: All entries in the abstract lists are freed. All the Route Dissemination routes are destroyed.

* Interface going down: for all entries in the Reachable list on that interface, the associated route is removed, and the entry is scheduled to be destroyed.

* Neighbor being removed from the ND list: if the entry is in the Reachable list the associated route is removed, and the entry is scheduled to be destroyed.

* Roaming: All entries in the Reachable list are set to not 'reported' and DelayNA is armed.

## 4. Forwarding

The fundamental mechanisms described in this draft build a DAG to enable communication from the LLN Router nodes to the LLN Border

Routers (upstream); a second mechanism informs LLN Routers about their children in the tree, hence enabling LLN Boarder Router to LLN Router communication (downstream) and node-to-node routing along the tree. While the previous sections focus on how routing information is disseminated throughout the LLN and used for routing, this section focuses on the forwarding policies used by LLN Routers.

Reliability can be increased by allowing for secondary next-hop nodes for upstream traffic, while downstream traffic is sent along the tree formed by route dissemination.

## 4.1. Upstream Forwarding

Forwarding in a LLN needs to account for requirements that are unusual in the IP world:

perfect loop freedom is a non-goal

the specification allows the wheel model where a packet circulates a bit around the destination till it finally makes it.





transient forwarding failure are commonplace

This specification introduces the capability for the layer 2 to give a packet back to layer 3 in order to try another adjacency.

Using the LLN Tree Discovery procedure, LLN Routers expose their path metrics using the Uniform Path Metric field in the TIO. Neighbor LLN Routers with a lesser depth in the tree then self are forwarding parents. Neighbor LLN Routers with a same depth in the tree are siblings. Forwarding via parents ensures a loop free operation whereas forwarding via siblings may not be loopfree unless additional measures are taken.

The approach taken in this specification is to favor forwarding via parents but enable forwarding via siblings as a backup option. Preferring the parents enables a forwarding gradient towards the LBR that limits the chances of multiple consecutive hops over siblings. This specification also prevents from returning a packet back to the neighbor that just passed it. This simple rule coupled with the

forwarding gradient protect against loops for a vast majority of cases, and the specification relies on a appropriate setting of the TTL in a given deployment to protect against meltdowns.

In more details:

- A LLN router MUST send upstream data to its forwarding parent with smallest metric. Note that, depending on the way the routing protocol determines this metric, and the dynamics of the tree, the best forwarding parent at a given point of time is not necessarily the parent with the smallest depth or the parent in the logical tree defined by the Tree Discovery procedure.

- If the transmission of an upstream packet to that preferred parent fails (due to a node or link failure, or mobility), the LLN router MAY attempt to forward the packet again via other parents, as ordered by best metric.

- If the transmission to both primary and secondary forwarding parents fails, the LLN Router MAY forward the packet via siblings, as ordered by best metric.

- When the transmission fails and the packet is retried via a different neighbor, the router MUST decrease the TTL by one.

In order to enable these rules, a LLN router maintains a blacklist per packet being forwarded that contains:

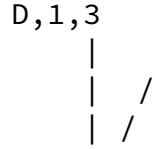




- the neighbor that forwarded the packet to self

- neighbors to which forwarding of this packet failed

These rules are illustrated in the following figure which represents a subset of an LLN.



C,2,9--- A,2,8

An LLN Router is identified by <Id,Depth,Metric>. LLN Router A has three neighbors B,C,D. D is A's primary forwarding parent as it is the neighbor with the smallest Metric amoung neighbors with smaller depth. If transmission to D fails, A sends the packet to B, which is of smaller depth. If transmission to B fails, A transmits to C. Because C is at the same depth as A, a blacklisting policy is used to avoid that C retransmits to A.

## 4.2. Downstream Forwarding

Downstream routing using LLN fundamental mechanisms can occur using either hop-by-hop state, source routing or a combination of them (loose source route). By default the LLN Dissemination mechanism builds up hop-by-hop distance-vector routing information in each of the routers along the tree up to the root for each address, prefix or group ID.

Source routing can optionally be supported by either requesting a route record header from a node, or by having nodes send periodic route record headers up to the root. Route Dissemination also allows a compression of the Routing header when the routes match the topology as traced by Record Route on a per packet basis. In particular, if a Route Dissemination route exists to the first entry in the Record Route header via the source of the packet, then the router can override the source of the packet with its address without adding the original source to the Record Route. At that point, the routing header operation becomes loose, in other words an hybrid between transparent hop-by-hop (stateful) and source routing.

Therefore three different downstream techniques are supported:

- Hop-by-hop forwarding. When only partial route dissemination data reaches a LLN Border Router, it only knows the next-hop to a given LLN Router in the network. In this case, each LLN Router relaying





downstream data will select the next-hop according to the information it receives during route dissemination.

- Full source routing. When all the route dissemination data reaches a LLN Border Router, it one can choose to specify the full

list of LLN Routers to be traversed in each downstream data packet.

- Loose source routing. When the source route information is compressed because of existing state in the routers along the path.

# 5. Multicast Support

## 5.1. Overview

Wherever we mention <MLD>, one can read MLDv2,3 for IPv6. Doing IGMP over the LLN involves:

- LLN Border Router acting as a local Rendez-vous Point (RP) for the LLN and as source towards the Internet for all multicast flows started in the LLN.

- transporting <MLD> in Route Dissemination and recursive coalescence of the multicast requests.

## 5.2. Receiver Flow

The LBR is considered as a Rendezvous Point (RP) for all multicast flows issued from inside the LLN. Multicast packets are passed up the tree to the LBR.

Nodes talk <MLD> to their parent router. The parent router forward the registration and inject their own as a special type of RIO for multicast groups, towards the LBR. The LBR MAY participate to multicast in the infrastructure it is connected to and forward all the packets coming from the LLN.

Between the parent router and the LBR, <MLD> requests are transported in the RIO; each hop aggregates the requests in a fashion that is similar to proxy IGMP, but this happens recursively between child node to parent router up to the LBR. On the way, multicast routing states are installed in each router from the receiver to the root, enabling multicast routing down the LLN tree.

### 5.3. Source flow

As a Node, the source is unaware of the ROLL protocol, and it uses standard protocols with the router (say in IPv6: Neighbor Discovery, <MLD> etc...). So when it has a multicast packet to send, the source just forwards it to its default router, which is the expected standard behavior. RRs on the way recursively forward to their parent. At each hop, if a multicast route indicates that a listener is reachable via another child (but that from which the packet was received) then the packet is duplicated and forwarded to that child down the tree.

If the LLN Border Router is configured to do so, it will source the packet to a real RP in the Internet.

## 6. Advanced Features

The fundamental mechanisms described in this document are sufficient to allow for upstream and downstream communication inside the LLN. They form a common basis upon which future LLN routing protocols can be designed. This section indicates some possible advanced features which can be integrated to increase efficiency for a particular useage scenarios.

### 6.1. Interaction with other routing protocols

While network design and specific use cases are out of scope for this document, it must be noted that the ROLL fundamentals mechanisms described herein might be used in conjunction with other routing protocols vin order to fulfill the requirements of a particular deployment. Here follows a non exhaustive series of examples illustrating such interactions.

#### 6.1.1. AODV/DYMO

In the example of a closed loop between a sensor and a switch, a constrained optimized route must be installed between the 2 devices.

Defining such a specific route is costly and should be performed on-demand when the bulk of the traffic is buffered data from source to sink.

A reactive MANET protocol such as AODV [RFC3561], DSR [RFC4728] or DYMO [I-D.ietf-manet-dymo] can be deployed to enable such routing, though the QoS-constrained approach for AODV is stalled as a draft ([I-D.perkins-manet-aodvqos]).

### 6.1.2. OSPF/OLSR

A federating backbone is the virtual root of a collection of trees that forms a single routing topology. If that topology shares a same prefix, a sensor device can move freely within the topology without renumbering.The 6LoWPAN backbone link is an example of such a federating backbone and in that case, the protocol that enables any to any reachability is simply IPv6 Neighbor Discovery [RFC4861].

In a generalized case with routing and multiple subnets, a traditional IGP such as OSPF [RFC2740] or a MANET protocol such as OLSR [RFC3626] can be deployed within the federating backbone between the LBR to advertise the routes learnt from the ROLL fundamentals dissemination protocol through the redistribution of route information.

In turn, the routed federating backbone is just the instantiation at Depth 0 of the more general concept of beltlines. A beltline is a set of routers of a same depth in a same tree that form a subarea where an IGP is run and route information from the LLN Route Dissemination protocol is redistributed. This creates routes around the root and reduces the load that routing along the tree imposes on the lower depth of the tree.

Note that in turn, beltline routes ARE NOT redistributed into LLN Route Dissemination information. As a result, the beltlines routes are orthogonal to the route dissemination routes, and they should never collide, which optimizes the value of the control plane of the combination.

Beltline routes should be used with caution in order to maintain stability and optimize the resulting routes:

- beltline routes should only be used when a certain topological stability was asserted

- using beltline routes discourages the reorganization of the tree, mostly when that causes a router to change its depth

- a divide and conquer approach to limit the size of a beltline enables to manage the cost of the control plane

- o a beltline of depth 2 or more should be an arc as opposed to full circle.In the example of a closed loop between a sensor and a switch, a constrained optimized route must be installed between the 2 devices.





### 6.1.3. MIP6/NEMO

MIP6 [RFC3775]and NEMO [RFC3963] enables a subtree to move away from the tree and maintain reachability as if the nodes in the subtree were still located in their topologically correct position. This can be useful when a RIO aggregation is performed (see Section 6.6) to enable reachability of a stray device. MIP6 be also be useful to enable a mobile display device such as a PDA to keep accessing a sensor network remotely without injecting the sensor network prefix into the infrastructure for security reasons.

## 6.2. Route Optimization

Whereas upstream and downstream communication is made possible by the fundamental mechanisms described in this document, applications may require more require traffic engineering, which may include:

### 6.2.1. Node-to-node routing

Node-to-node routing is ensured along the tree by the Route Dissemination protocol, and the packets flow via he first common parent. This can be optimized if the LLN Border Router has a clear view of the topology (see 'Offline Path Computation' section). In this case, the LLN Border Router can indicate the direct path between both LLN Routers, calculated offline, to the source, the destination, or both. This technique induces a trade-off between multi-hop route efficiency and signaling overhead to setup this direct node-to-node path for instance as suggested in Section 6.1.1.

### 6.2.2. Offline Path Computation

Whereas nodes might not have the capacity to store and manage enough information to perform constrained routing, it is possible for node to report there neighborhood information to the LLN Border routers. LLN Border routers can then share their partial topology databases

and get a full picture of the network.

From there, it is possible to get LLN Border routers to compute shorter or constrained paths and either distribute them (e.g. LDP) or pass the source route information to the end nodes.

An OSPF example of that goes like this. Nodes run HELLO or similar, and send their LSA in unicast to their LLN Border routers. The LLN Border routers act as proxy for the nodes and share those LSAs with other LLN Border routers over the backbone. At some point they converge and an LLN Border router will run SPF on behalf of all its registered nodes, one at a time. The SPF computation should end at a certain distance from the node for which it makes more sense to go





through the backbone anyway. Then the LLN Border router sends the set of routes to the node as an new topology that can be used in a MTR fashion.

### 6.2.3. Graph forwarding

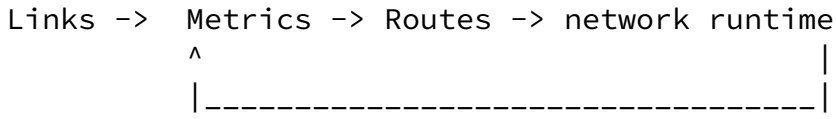
Distance Vector and Link State routing protocols are traditionally designed in terms of:

Links -> Metrics -> Routes -> network runtime

Unless traffic engineering kicks in, either the routes are established over the shortest path and the alternate links are wasted or the traffic is load balanced in a fashion that represents the ratio of costs as opposed to the ratio of capacity of the paths.

Also, the runtime of the network is opaque to the forwarding plane, so the only way to guarantee some end-to-end bandwidth for a class of traffic is to blindly reserve it, leading to even more waste of bandwidth when the reservation is not fully utilized.

In order to optimize the network utilization, it would be beneficial to detect the saturation of the shortest path and load balance the extra traffic over alternate routes. In the case of ROLL, it is also critical to be able to make a reroute decision on a per packet basis when hop by hop retries are exhausted. Arpanet introduced a feedback loop into the routing protocol by making the metrics dynamic:




But this approach was unsuccessful, causing instabilities and disrupting the network. With dynamic metrics, the duration of the convergence time - or frozen time -,increases with the number of links and the frequency of the metric updates. During that time, the response of the network is undefined and temporary loops occur.

An approach to solve this problem is having 2 independent sets of metrics: In one hand, the topological metrics that are rather static and mostly administratively set; and in the other hand the volatile metrics that are based on dynamic measurements of the network characteristics.

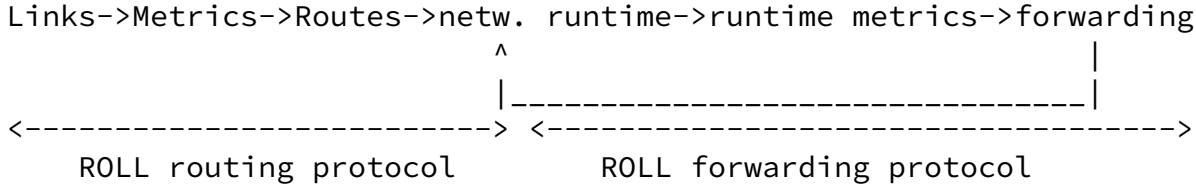
The topological metrics are used by the ROLL routing protocol to initially build the tree as described in this specification. The





volatile metrics are then used by a forwarding protocol to balance the traffic for that destination over the upstream links, thus modifying the way the graph is being used in runtime, without changing its structure.

To get there, the control plane operates in 2 phases, in a lollipop fashion:




The ROLL fundamentals proposal builds shortest path trees to the exits but adds the capability to forward over another branch if sending a packet to a parent fails, either via any alternate parent or a sibbling. So the paths that we really want to monitor are along the tree itself and one hop away from the tree. To get there, the root emits a beacon that is multicasted down the tree and heard one

hop away. That beacon gathers the metrics that will be used for alternate parents and sibblings selection and nodes keep track of the beacon they hear for all the parents and sibblings they want to track. From the beacon, they can infer the quality of the path through all the alternates and compare them.

## 6.3. Density

In a dense environment, it is useless that all routers that can provide backhauling service actually do so; in practice, limiting the number of routers that accept attached nodes saves memory in the attached nodes and reduces the cost of signalling. Also, limiting the number of forwarding LLN Routers in the tree improves the multicast operations.

Algorithms such a Trickle could be used by a LLN Router to decide to stop providing its access services for attached nodes if there are a number of neighboring routers that provide similar services. The simplest abstraction of such similarity is that a multiple routers advertising a same depth, though such a simple similarity does not address the specifics of a router selection in the plugins. In a more general fashion, a LLN Router can associate the concept of similarity with the characteristics of its own parent router selection plug in.





## 6.4. Digraph Dissemination

The fundamental techniques described in this draft coverlays a tree for source/sink traffic over the physical topology. This tree could be converted into a (bi)graph with additional overhead. A LLN Router would therefore send route dissemination data to both its primary and secondary forwarding parents, hence informing a LLN Border Router of disjoint paths. This makes sense in applications where the gains in increase downstream reliability outweigh the additional signaling overhead.

## 6.5. Multiple LBRs and Trees

The ROLL tree discovery technique propagates increasing depths and

metrics throughout the network; upstream messages travel on a decreasing metric path back to the ROLL border router. When the LLN features multiple LBRs, the following options appear:

- If the different LBRs share the same TreeID, a LLN Router implicitly sends its upstream data to the LBR which is closest in terms of aggregated metric. This should be used whenever LBR play the same role.

- Different LBRs may choose to use different TreeIDs. In this case, a LLN Router is part of multiple trees, one for eachTreeID. When sending an upstream message, a LLN Router chooses on which TreeID it wishes to send, i.e. to which LBR.

- A hybrid case can exist in which some LBRs share the same TreeID while others have their dedicated tree ID.

An alternative when having multiple LBR is to construct multiple trees (e.g. one for each LBR) and choose a default tree for forwarding data. Using an alternate tree is possible only when labeling the data packet accordingly; an unlabeled packet is forwarded on the default tree.

## 6.6. Aggregation for Route Dissemination

Aggregation of prefixes on a same router

When deploying an router with multiple interfaces, it makes sense to assign an aggregation prefix (shorter than /64) to the router and partition it as /64 prefixes over the router interfaces. An router that owns a contiguous set of prefixes should only report the aggregation of these prefixes through Route Dissemination.





Aggregation of prefixes by a parent acting as ROLL Home

There are also a number of cases where a ROLL aggregation is shared within a toon of LLN Routers. For instance, a toon formed by firefighters and their commander. In that case, it is still possible to use aggregation techniques with Route Dissemination and improve its scalability. In that case, the commander is

configured as the Route Dissemination aggregator for the group prefix. In run time, it absorbs the individual RIO information it receives from the toon members down its subtree and only reports the aggregation up the TD tree. This works fine when the whole toon is attached within the commander's subtree.

But other cases might occur for which additional support is required:

1. the commander is attached within the subtree of one of its toon members.

2. A toon member is somewhere else within the TD tree.

3. A toon member is somewhere else in the Internet.

In all those cases, a node situated above the commander in the TD tree but not above the toon member will see the advertisements for the aggregation owned by the commander but not that of the individual toon member prefix. So it will route all the packets for the toon member towards the commander, but the commander will have no route to the toon and will fail to forward.

## 6.7. Advanced Forwarding

A blacklisting policy can be used to avoid routing loops when an upstream data packet is sent between neighbor LLN Routers of the same depth. Alternatively, more general techniques can be used to avoid loops. One is to record the sequence of already traversed nodes in the data packet as it travels along a multi-hop path. When receiving a packet, a LLN Router may know whether it has already relayed that packet; if yes, it can know from which neighbors it had received it and to which it had sent. A distributed version of depth first search can then be used to avoid routing loops. This extension enables upstream packets to be sent to neighbors with a larger depth.

# 7. Security Considerations

As this draft suggests the use of new options carried in ICMP ND messages; the same security considerations as in [RFC4861] apply, in

particular with regards to the use of Secure ND [RFC3971] to protect against address theft. Additionally link-layer security should be applied in the case of 6LoWPAN where SeND is not typically possible.

## 8. IANA Considerations

This draft would require two new ICMP options for use with ND: the Tree Information Option (TIO) and the Route Information Option (RIO).

## 9. Acknowledgments

The authors would like to thank Robert Assimiti, Kris Pister, Mischa Dohler, Julien Abeille, Ryuji Wakikawa, Teco Boot, Patrick Wetterwald, Bryan Mclaughlin and Carlos J. Bernardos for useful design considerations.

## 10. References

### 10.1. Normative References

[RFC2460] Deering, S. and R. Hinden, "Internet Protocol, Version 6 (IPv6) Specification", RFC 2460, December 1998.

[RFC4944] Montenegro, G., Kushalnagar, N., Hui, J., and D. Culler, "Transmission of IPv6 Packets over IEEE 802.15.4 Networks", RFC 4944, September 2007.

### 10.2. Informative References

[I-D.ietf-manet-dymo]
Chakeres, I. and C. Perkins, "Dynamic MANET On-demand (DYMO) Routing", draft-ietf-manet-dymo-17 (work in progress), March 2009.

[I-D.ietf-roll-building-routing-reqs]
Martocci, J., Riou, N., Mil, P., and W. Vermeylen, "Building Automation Routing Requirements in Low Power and Lossy Networks", draft-ietf-roll-building-routing-reqs-05 (work in progress), February 2009.

[I-D.ietf-roll-home-routing-reqs]
Porcu, G., "Home Automation Routing Requirements in Low Power and Lossy Networks", draft-ietf-roll-home-routing-reqs-06 (work in progress), November 2008.

[I-D.ietf-roll-indus-routing-reqs]
Networks, D., Thubert, P., Dwars, S., and T. Phinney, "Industrial Routing Requirements in Low Power and Lossy Networks", draft-ietf-roll-indus-routing-reqs-04 (work in progress), January 2009.

[I-D.ietf-roll-terminology]
Vasseur, J., "Terminology in Low power And Lossy Networks", draft-ietf-roll-terminology-00 (work in progress), October 2008.

[I-D.ietf-roll-urban-routing-reqs]
Dohler, M., Watteyne, T., Winter, T., Barthel, D., Jacquenet, C., Madhusudan, G., and G. Chegaray, "Urban WSNs Routing Requirements in Low Power and Lossy Networks", draft-ietf-roll-urban-routing-reqs-05 (work in progress), March 2009.

[I-D.perkins-manet-aodvqos]
Perkins, C. and E. Belding-Royer, "Quality of Service for Ad hoc On-Demand Distance Vector Routing", draft-perkins-manet-aodvqos-01 (work in progress), November 2001.

[RFC2740] Coltun, R., Ferguson, D., and J. Moy, "OSPF for IPv6", RFC 2740, December 1999.

[RFC3561] Perkins, C., Belding-Royer, E., and S. Das, "Ad hoc On-Demand Distance Vector (AODV) Routing", RFC 3561, July 2003.

[RFC3626] Clausen, T. and P. Jacquet, "Optimized Link State Routing Protocol (OLSR)", RFC 3626, October 2003.

[RFC3775] Johnson, D., Perkins, C., and J. Arkko, "Mobility Support in IPv6", RFC 3775, June 2004.

[RFC3963] Devarapalli, V., Wakikawa, R., Petrescu, A., and P. Thubert, "Network Mobility (NEMO) Basic Support Protocol", RFC 3963, January 2005.

[RFC3971] Arkko, J., Kempf, J., Zill, B., and P. Nikander, "SEcure Neighbor Discovery (SEND)", RFC 3971, March 2005.

[RFC4728] Johnson, D., Hu, Y., and D. Maltz, "The Dynamic Source Routing Protocol (DSR) for Mobile Ad Hoc Networks for IPv4", RFC 4728, February 2007.





[RFC4861] Narten, T., Nordmark, E., Simpson, W., and H. Soliman, "Neighbor Discovery for IP version 6 (IPv6)", RFC 4861, September 2007.

## Authors' Addresses

Pascal Thubert
Cisco Systems
Village d'Entreprises Green Side
400, Avenue de Roumanille
Batiment T3
Biot - Sophia Antipolis 06410
FRANCE

Phone: +33 4 97 23 26 34
Email: pthubert@cisco.com

Thomas Watteyne
UC Berkeley
497 Cory Hall #1774
Berkeley Sensor & Actuator Center
Berkeley, California 94720-1774
USA

Phone: +1 (510) 333-4437
Email: watteyne@eecs.berkeley.edu

Zach Shelby
Sensinode
Kidekuja 2
Vuokatti 88600
FINLAND

Phone: +358407796297
Email: zach@sensinode.com





Dominique Barthel
Orange Labs
28 chemin du Vieux Chene, BP98
BP98
Meylan 38243
FRANCE

Phone: +33476764522
Email: dominique.barthel@orange-ftgroup.com