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Wired and Wireless IPv6 Neighbor Discovery Optimizations
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Abstract

IPv6 Neighbor Discovery (RFC 4861) protocol has been designed for neighbor's address resolution, unreachability detection, address autoconfiguration, router advertisement and solicitation. With the progress of Internet adoption on various industries including home, wireless, M2M and cellular networks there is a desire for optimizing the legacy IPv6 Neighbor Discovery protocol. This document describes a method of optimization by reducing multicast messages and introducing an IPv6 address Registration mechanism. The optimization of IPv6 Neighbor Discovery protocol is useful for Wirless and low-power IPv6 networks and as well as Data Centers and Home Networks. The solution is capable of handling existing legacy IPv6 nodes in the network with local mobility.

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1. Introduction

Conceptually, IPv6 multicast messages are supposed to avoid broadcast messages, but in practice, the multicast operation at the link level is that of a broadcast nevertheless. This did not matter much at the time ND [ND] was originally designed, when an Ethernet network was more or less a single shared wire, but since then, large scale switch fabrics, low power sleeping devices, mobile wireless/cellular devices and virtual machines have changed the landscape dramatically.

In a modern switch fabric, a number of intermediate devices (such as switches, routers and security middle boxes) host IPv6 State Maintaining Entities (SMEs) holding information such as the location of an IPv6 address or its mapping with a MAC address. Such intermediate devices include Wireless Controllers that terminate a overlay tunnel and rapidly re-enable reachability for mobile devices(L2/L3), Network edge devices performing subscriber access, network devices that protect the ownership of an IPv6 address, Overlay networks in data centers, Home Networks for IPv6 clients.

In general, there is a need for enhancing the IPv6 ND [ND] to make it less chatty and flexible to work with different types of networking elements, physical and virtual networks and at the same time maintaining the IPv6 states to avoid duplicates or denial of services.

1.1. Problem Areas

Specifically, the following are the issues with the IPv6 deployment in many wireless and high-density IPv6 subnets today:

o The periodic RA messages in IPv6 ND [ND], and NS/NA messages require all IPv6 nodes in the link to be in listening mode even when they are in idle cycle. It requires energy for the sleepy nodes which may otherwise be sleeping during the idle period. Non-sleepy nodes also spends more energy since they are in continuous listening mode. With the explosion of Internet-of-things and machine to machine communication, more and more devices would be using IPv6 addresses in the near future.

o With WIFI, a multicast message will consume the wireless link on all Access Points around a switched fabric and will be transmitted at the lowest speed possible in order to ensure the maximum reception by all wireless nodes. This means that in an environment where bandwidth is scarce, a single multicast packet may consume the bandwidth for hundreds of unicast packets. Sadly, IPv6 ND is a major source of multicast messages in wireless devices, since such messages are triggered each time a wireless device changes its point of attachment.

o In a datacenter, where VM mobility and VM address reslution also trigger storms of IPv6 ND multicast messages, which become a major hassle as the number of VM may scale to the tens of thousands in a large Data Center. At the IETF, a WG discusses such problems with Address Resolution in Massive Datacenters (ARMD).

The following paragraph elaborates the source of all the multicast messages in IPv6 ND.

Following power-on and initialization of the network in IPv6 Ethernet networks, a node joins the solicited-node multicast address on the interface and then performs duplicate address detection (DAD) for the acquired link-local address by sending a solicited-node multicast message to the link. After that it sends multicast router solicitation (RS) messages to the all-router address to solicit router advertisements. Once the host receives a valid router advertisement (RA) with the "A" flag, it autoconfigures the IPv6 address with the advertised prefix in the router advertisement (RA). Besides this, the IPv6 routers usually send router advertisements periodically on the network. RAs are sent to the all-node multicast address. The minimum RA interval range can be 3sec to 600sec depending on applications. Nodes send Neighbor Solicitation (NS) and Neighbor Advertisement (NA) messages to resolve the IPv6 address of the destination on the link. These NS/NA messages are also often multicast messages and it is assumed that the node is on the same link and relies on the fact that the destination node is always powered and generally available.

1.2. Overview of the basic ND Optimization

In a nutshell, the following basic optimizations are made from the original IPv6 Neighbor Discovery protocol [ND]:

- o Adds Node Registration at the default subnet-router
- o Introduces a EUI-64 identifier for identification during initiation
- o Does not require unsolicited periodic Router Advertisements
- o No multicast messages required for address resolution and DAD for non-link-local IP addresses
- o Introduces a short-lived temporary NCE entry for unregistered nodes that turns into a regular NCE upon registration
- o Supports mixed mode operations where legacy IPv6 nodes and enahnced optimized routers can co-exist during the transition period.

EUI-64 identifiers are recommended as unique Interface Identifiers, however if the network is isolated from the Internet, uniqueness of the identifiers may be obtained by other mechanisms such as a random number generator with lowest collision rate. Although, the ND

optimization [6LOWPAN-ND] applies to 6LoWPAN [LOWPAN] networks, the concept is mostly applicable to power-aware IPv6 networks. Therefore, this document generalizes the address registration and multicast reduction in [6LOWPAN-ND] to all IPv6 links.

Thus optimizing the regular IPv6 Neighbor Discovery [ND] to minimize total number of related signaling messages without losing generality of Neighbor Discovery, autoconfiguration and reliable host-router communication, are desirable in any modern IPv6 networks such as Home, Enterprise networks, Data Centers and Operator's Cellular/ Wireless networks.

The optimization will be highly effective for links and nodes which do not support multicast and as well as for a multicast network without MLD snooping switches. Moreover, in the MLD-snooping networks the MLD switches will deal with less number of multicasts.

The goal of this document is to provide an efficient Neighbor Discovery Protocol in classic IPv6 subnets in wireless/wired links. In the process, the node registration method is also deemed to be useful for preventing Neighbor Discovery denial of service (ND DOS) attacks.

The proposed changes can be used in two different ways. In one case all the hosts and routers on a link implement the new mechanisms, which gives the maximum benefits. In another case the link has a mixture of new hosts and/or routers and legacy [RFC4861] hosts and routers, operating in a mixed-mode providing some of the benefits.

In the following sections the document describes the basic operations of registration methods, optimization of Neighbor Discovery messages, interoperability with legacy IPv6 implementations and provides a section on use-case scenarios where it can be typically applicable. This document also describes an optional feature for enabling node mobility in the LLN network using backbone routers(BBR) or multiple default subnet routers. This optional feature generates a sequence ID by the host in the registration message for deploying some routing protocols (example: RPL [RFC6550]) with reliability in the LLN.

2. Definition Of Terms

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC2119].

multi-level Subnets:
A wireless link determined by one IPv6 off-link prefix in a network where in order to reach a destination with same prefix a packet may have to travel through one or more 'intermediate' routers which relay the packet to the next 'intermediate' router or the host in its own.

Border Router(BR):
A border router is typically located at the junction of Internet and Home Network. An IPv6 router with one interface connected to an IPv6 subnet and other interface connecting to a non-classic IPv6 interface such as 6LoWPAN interface. A Border router is usually the gateway between the IPv6 network and Internet.

Backbone:
This is an IPv6 transit link that interconnects 2 or more Low Power Lossy Networks (LLNs). It is expected to be deployed as a high speed backbone in order to federate a potentially large set of LLN nodes. Also referred to as a LLN backbone or Backbone network in this document.

Backbone Router:
An IPv6 router that federates the LLN using a transit link as a backbone. A BBR acts as a 6LoWPAN Border Router (6LBR) and an Efficiency Aware Default Router (NEAR).

Efficiency-Aware Network:
An Efficiency-Aware network is composed of network elements that are sensitive to energy usage or number of signaling messages in the network. An efficiency-aware network may also contain links that do not support multicast or it does not have MLD snooping capabilities and yet the network likes to communicate most efficiently with minimum number of signaling messages. Data center networks with virtual machines, cellular IPv6 networks, any IPv6 networks with energy-sensitive nodes are examples of Efficiency-Aware networks.

IPv6 ND-efficiency-aware Router(NEAR):
The default Router of the single hop IPv6 subnet. This router implements the optimizations specified in this document. This router should be able to handle both legacy IPv6 nodes and nodes that sends registration request.

Efficiency-Aware Host(EAH):
A host in a IPv6 network is considered a IPv6 node without routing and forwarding capability. The EAH is the host which implements the host functionality for optimized Neighbor Discovery mentioned in this document.

Legacy IPv6 Host:
A host in a IPv6 network is considered a IPv6 node without routing and forwarding capability and implements RFC 4861 host functions.

Legacy IPv6 Router:
An IPv6 Router which implements RFC 4861 Neighbor Discovery protocols.

EUI-64:
It is the IEEE defined 64-bit extended unique identifier formed by concatenation of 24-bit or 36-bit company id value by IEEE Registration Authority and the extension identifier within that company-id assignment. The extension identifiers are 40-bit (for 24-bit company-id) or 28-bit (for the 36-bit company-id) respectively.

LLN:
It is a low power and lossy network where nodes are typically constrained in system resources and energy, for instance battery powered nodes. Alternately LLN could be a network of line-powered nodes with radio links with lossy characteristics. Wifi, ZigBee, Celular networks are examples of such a network.

Extended LLN:
This is the aggregation of multiple LLNs as defined in [RFC4919] interconnected by a Backbone Link via Backbone Routers and forming a single IPv6 link.

3. Assumptions for efficiency-aware Neighbor Discovery

- The efficiency-aware nodes in the network carry unique interface ID in the network in order to form the auto-configured IPv6 address uniquely. An EUI-64 interface ID required for global communication.
- All nodes are single IPv6-hop away from their default router in the subnet.
- /64-bit IPv6 prefix is used for Stateless Auto-address configuration (SLAAC). The IPv6 Prefix may be distributed with Router Advertisement (RA) from the default router to all the nodes in that link.
- The efficiency-aware node MAY maintain a sequence counter in permanent memory according to section 7 of RFC 6550.

4. The set of Requirements for efficiency and optimization

- Node Registration: Node initiated Registration and address allocation is done in order to avoid periodic multicast Router Advertisement messages and often Neighbor Address resolution can be skipped as all packets go via the default router which now knows about all the registered nodes. Node Registration enables reduction of all-node and solicited-node multicast messages in the subnet.

- o Address allocation of registered nodes [ND] are performed using IPv6 Autoconfiguration [AUTOCONF].
- o Host initiated Registration and Refresh is done by sending a Router Solicitation and then a Neighbor Solicitation Message using Address Registration Option (described below).
- o The node registration may replace the requirement of doing Duplicate Address Detection.
- o Sleepy hosts are supported by this Neighbor Discovery procedures as they are not woken up periodically by Router Advertisement multicast messages or Neighbor Solicitation multicast messages. Sleepy nodes may wake up in its own schedule and send unicast registration refresh messages when needed.
- o Since this document requires formation of an IPv6 address with an unique 64-bit Interface ID(EUI-64) is required for global IPv6 addresses, if the network is an isolated one and uses ULA [ULA] as its IPv6 address then the deployment should make sure that each MAC address in that network has unique address and can provide a unique 64-bit ID for each node in the network.
- o A /64-bit Prefix is required to form the IPv6 address.
- o MTU requirement is same as IPv6 network.

5. Basic Operations

In the efficient-nd IPv6 Network, the NEAR routers are the default routers for the efficiency-aware hosts (EAH). During the startup or joining the network the host does not wait for the Router Advertisements as the NEAR routers do not perform periodic multicast RA as per RFC 4861. Instead, the EAH sends a multicast RS to find out a NEAR router in the network. The RS message is the same as in RFC 4861. The advertising routers in the link responds to the RS message with RA with Prefix Information Option and any other options configured in the network. If EAH hosts will look for a RA from a NEAR (E-flag) and choose a NEAR as its default router and consequently sends a unicast Neighbor Solicitation Message with ARO option in order to register itself with the default router. The EAH does not do Duplicate Address Detection or NS Resolution of addresses. NEAR maintains a binding of registered nodes and registration life-time information along with the neighbor Cache information. The NEAR is responsible for forwarding all the messages from its EAH including on-link messages from one EAH to another. For details of protocol operations please see the sections below.

When a IPv6 network consists of both legacy hosts and EAH, and if the NEAR is configured for 'mixed mode' operation, it should be able to handle Address Registration Option(ARO) requests and send periodic RA. Thus it should be able to serve both efficiency-aware hosts and legacy hosts. Similarly, a legacy host compatible EAH falls back to

RFC 4861 host behavior if a NEAR is not present in the link. See the section on 'Mixed Mode Operations' for details below.

6. Applicability Statement

This document aims to guide implementers to choose an appropriate IPv6 neighbor discovery and Address configuration procedures suitable for any efficient IPv6 network. These optimizations are equally useful for the energy-sensitive, non-multicast links and for classical IPv6 networks i.e. home networks, Data-Center IPv6 overlay networks where saving Neighbor Discovery messages will reduce cost and increase bandwidth availability.

The address registration mechanism and associated extension to the Neighbor Discovery protocol allow a low-power host to move between the LLN and the classic IPv6 networks as well as movement from one Border Router registration area to another while staying within the same IPv6 subnet.

Note that the specification allows 'Mixed-mode' operation in the efficiency-aware nodes for backward compatibility and transitioning to a complete efficiency-aware network of hosts and routers. Though the efficiency-aware only nodes will minimize the ND signaling and DOS attacks in the LAN.

Applicability of this solution is limited to the legacy IPv6 nodes and subnets and it optimizes the generic IPv6 signaling activities at network layer. However, further optimization at the application layers are possible for increased efficiency based on particular use-cases and applications.

7. New Neighbor Discovery Options and Messages

This section will discuss the registration and de-registration procedure of the hosts in the network.

7.1. Address Registration Option

The Address Registration Option(ARO) is useful for avoiding Duplicate Address Detection messages since it requires a unique EUI-64 ID for registration. The address registration is used for maintaining reachability of the node or host by the router. This option is almost the same ARO as in [6LOWPAN-ND]. A Transaction ID field and a corresponding bit have been introduced in order to detect duplicate address registration and local mobility of a node.

The routers keep track of host IP addresses that are directly reachable and their corresponding link-layer addresses. This is useful for lossy and lowpower networks(LLN) and as well as wired IPv6 networks. An Address Registration Option (ARO) can be included in unicast Neighbor Solicitation (NS) messages sent by hosts. Thus it can be included in the unicast NS messages that a host sends as part of Neighbor Unreachability Detection to determine that it can still reach a default router. The ARO is used by the receiving router to reliably maintain its Neighbor Cache. The same option is included in corresponding Neighbor Advertisement (NA) messages with a Status field indicating the success or failure of the registration. This option is always host initiated.

The ARO is required for reliability and power saving. The lifetime field provides flexibility to the host to register an address which should be usable (the reachability information may be propagated to the routing protocols) during its intended sleep schedule of nodes that switches to frequent sleep mode.

The sender of the NS also includes the EUI-64 of the interface it is registering an address from. This is used as a unique ID for the detection of duplicate addresses. It is used to tell the difference between the same node re-registering its address and a different node (with a different EUI-64) registering an address that is already in use by someone else. The EUI-64 is also used to deliver an NA carrying an error Status code to the EUI-64 based link-local IPv6 address of the host.

When the ARO is used by hosts and SLLA option MUST be included [except for the point-to-point links (example: IP-in-IP tunnel)] and the target address for to-be registered node MUST be the IPv6 source address of the Neighbor Solicitation message.

Note that a node should be able to register with a default router with multiple IPv6 addresses (including privacy addresses).

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     Type      |   Length = 2  |    Status     |   Reserved    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   Reservd   |T|  TID          |     Registration Lifetime     |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+               EUI-64 or equivalent                            +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Fields:

Type: 33 (See [6LOWPAN-ND])

Length: 8-bit unsigned integer. The length of the option in units of 8 bytes. Always 2.

Status: 8-bit unsigned integer. Indicates the status of a registration in the NA response. MUST be set to 0 in NS messages. See below.

Reserved: This field is unused. It MUST be initialized to zero by the sender and MUST be ignored by the receiver.

TID: 8-bit integer. It is a transaction id maintained by the host and incremented with each registration. it is recommended that the node maintains a persistent storage for TID. TID is used as a sequence counter to detect the most recent registration request from a host and its mobility within the same subnet across multiple default Border Routers. Its operation follows section 7 of RPL [RFC6550] for sequence counters.

Registration Lifetime: 16-bit unsigned integer. The amount of time in a unit of 60 seconds that the router should retain the Neighbor Cache entry for the sender of the NS that includes this option.

EUI-64: 64 bits. This field is used to uniquely identify the interface of the registered address by including the EUI-64 identifier assigned to it unmodified.

T bit: One bit flag. Set if the TID octet is present for processing.

The Status values used in Neighbor Advertisements are:

Status	Description
0	Success
1	Duplicate Address
2	Neighbor Cache Full
3	Registration Ownership Response
4-255	Allocated using Standards Action [RFC2434]

Table 1

7.2. Refresh and De-registration

A host SHOULD send a Registration message in order to renew its registration before its registration lifetime expires in order to continue its connectivity with the network. If anytime, the node decides that it does not need the default router's service anymore,

it MUST send a de-registration message - i,e, a registration message with lifetime being set to zero. A mobile host SHOULD first de-register with the default router before it moves away from the subnet.

7.3. A New Router Advertisement Flag

A new Router Advertisement flag [RF] is needed in order to distinguish a router advertisement from a efficiency-aware default router or a legacy IPv6 router. This flag is ignored by the legacy IPv6 hosts. EAH hosts use this flag in order to discover a NEAR router if it receives multiple RA from both legacy and NEAR routers.

```
 0 1 2 3 4 5 6 7
+-+-+-+-+-+-+-+-+
|M|O|H|Prf|P|E|R|
+-+-+-+-+-+-+-+-+
```

The 'E' bit above MUST be 1 when a IPv6 router implements and configures the efficiency-aware Router behavior for Neighbor Discovery as per this document. All other cases the E bit MUST be 0.

The legacy IPv6 hosts will ignore the E bit in RA advertisement. All EAH MUST look for E bit in RA in order to determine the efficiency-aware support in the default router in the link.

7.4. The Transaction Identification(TID)

The TID field is used together with age of a registration for arbitration between two routers (default or backbone) to ensure freshness and ownership of the registration of a given target address. Same value of TID indicates that both states of registration are valid. In case of a mismatch between comparable TIDs, the most recent TID wins. The TID definition used in section 6.4.1 of RFC 6550 for DAOSequence number would be applicable for here for TID in ARO message.

It is 8 bit field. TID is generated by the host at the time of a new registraton request.

This document assumes that an implementation will have configuration knobs to determine whether it is running in classical IPv6 ND [ND] or Efficiency Aware ND (this document) mode or both(Mixed mode).

8. Efficiency-aware Neighbor Discovery Messages

Router Advertisement(RA): Periodic RAs SHOULD be avoided. Only solicited RAs are RECOMMENDED. An RA MUST contain the Source Link-layer Address option containing Router's link-layer address (this is optional in [ND]. An RA MUST carry Prefix information option with L bit being unset, so that hosts do not multicast any NS messages as part of address resolution. A new flag (E-flag) is introduced in the RA in order to characterize the efficiency-aware mode support. Unlike RFC4861 which suggests multicast Router Advertisements, this specification optimizes the exchange by always unicasting RAs in response to RS. This is possible since the RS always includes a SLLA option, which is used by the router to unicast the RA.

Router Solicitation(RS): Upon system startup, the node sends a multicast or link broadcast (when multicast is not supported at the link-layer) RS to find out the available routers in the link. An RS may be sent at other times as described in section 6.3.7 of RFC 4861. A Router Solicitation MUST carry Source Link-layer Address option except for the point-to-point links. Since no periodic RAs are allowed in the efficiency-aware IPv6 network, the host may send periodic unicast RS to the routers. The time-periods for the RS varies on the deployment scenarios and the Default Router Lifetime advertised in the RAs.

Default Router Selection: Same as in section 6.3.6 of RFC 4861[ND].

Neighbor Solicitation (NS): Neighbor solicitation is used between the hosts and the default-router as part of NUD and registering the host's address(es). An NS message MUST use the Address Registration option in order to accomplish the registration.

Neighbor Advertisement (NA): As defined in [ND] and ARO option.

Redirect Messages: A router SHOULD NOT send a Redirect message to a host since the link has non-transitive reachability. The host behavior is same as described in section 8.3 of RFC 4861[ND], i,e. a host MUST NOT send or accept redirect messages when in efficiency-aware mode.

Same as in RFC 4861[ND]

MTU option: As per the RFC 4861.

Address Resolution: No NS/NA are sent as the prefixes are treated as off-link. Thus no address resolution is performed at the hosts. The routers keep track of Neighbor Solicitations with Address Registration options(ARO) and create an extended neighbor cache of reachable addresses. The router also knows the nexthop link-local address and corresponding link-layer address when it wants to route a packet.

Neighbor Unreachability Detection(NUD): NUD is performed in "forward-progress" fashion as described in section 7.3.1 of RFC 4861[ND]. However, if Address Registration Option is used, the NUD SHOULD be combined with the Re-registration of the node. This way no extra message for NUD is required.

9. Efficiency-aware Host Behavior

A host sends Router Solicitation at the system startup and also when it suspects that one of its default routers have become unreachable(after NUD fails). The EAH MUST process the E-bit in RA as described in this document. The EAH MUST use ARO option to register with the neighboring NEAR router.

A host SHOULD be able to autoconfigure its IPv6 addresses using the IPv6 prefix obtained from Router Advertisement. The host SHOULD form its link-local address from the EUI-64 as specified by IEEE Registration Authority and RFC 2373. If this draft feature is implemented and configured, the host MUST NOT re-direct Neighbor Discovery messages. The host is not required to join the solicited-node multicast address but it MUST join the all-node multicast address.

A host always sends packets to (one of) its default router(s). This is accomplished by the routers never setting the 'L' flag in the Prefix options.

The host is unable to forward routes or participate in a routing protocol. A legacy IPv6 Host compliant EAH SHOULD be able to fall back to RFC 4861 host behavior if there is no efficiency-aware router (NEAR) in the link.

The efficiency-aware host MUST NOT send or accept re-direct messages.

It does not join solicited node multicast address.

If the EAH is capable of generating TID and configured for this operation, the EAH MUST use the TID field and appropriate associated operation bits in the ARO message during registration and refresh.

In some cases, hosts may need to send MAX_RTR_SOLICITATIONS(3) to receive the reply back from the default router. In a lossy link or due to sleepy default router, the hosts may have to send more than 3 solicitations [Resilient-RS]. But this can easily increase the number of siganling traffic in the network. Thus it is RECOMMEDED that the EAH nodes start with the default MAX_RTR_SOLICITATION [ND] value in a low power network.

However, in some scenarios the packet loss resilient router solicitation method may be applicable [Resilient-RS].

10. The Efficiency Aware Default Router (NEAR) Behavior

The main purpose of the default router in the context of this document is to receive and process the registration request, forward packets from one neighbor to the other, informs the routing protocol about the un-availability of the registered nodes if the routing protocol requires this information for the purpose of mobility or fast convergence. A default router (NEAR) behavior may be observed in one or more interfaces of a Border Router(BR).

A Border Router normally may have multiple interfaces and connects the nodes in a link like a regular IPv6 subnet(s) or acts as a gateway between separate networks such as Internet and home networks . The Border Router is responsible for distributing one or more /64 prefixes to the nodes to identify a packet belonging to the particular network. One or more of the interfaces of the Border Router may be connected with the efficiency-aware hosts or a efficiency-aware router(NEAR).

The efficiency-aware default router MUST not send periodic RA unless it is configured to support both legacy IPv6 and efficiency-aware hosts. If the Router is configured for efficiency-aware hosts support, it MUST send Router Advertisements with E-bit flag ON and MUST NOT set 'L' bit in the advertisements.

The router SHOULD NOT garbage collect Registered Neighbor Cache entries since they need to retain them until the Registration Lifetime expires. If a NEAR receives a NS message from the same host one with ARO and another without ARO then the NS message with ARO gets the precedence and the NS without ARO is ignored. This behavior

protects the router from Denial Of Service attacks. Similarly, if Neighbor Unreachability Detection on the router determines that the host is UNREACHABLE (based on the logic in [ND]), the Neighbor Cache entry SHOULD NOT be deleted but be retained until the Registration Lifetime expires. If an ARO arrives for an NCE that is in UNCREACHABLE state, that NCE should be marked as STALE.

A default router keeps a cache for all the nodes' IP addresses, created from the Address Registration processing.

10.1. Router Configuration Modes

An efficiency-aware Router(NEAR) MUST be able to configure in efficiency-aware-only mode where it will expect all hosts register with the router following RS; thus NEAR will not support legacy hosts. However, it will create legacy NCE for the routers in the network assuming that the routers do not register with it. This mode is able to prevent ND flooding on the link.

An efficiency-aware Router(NEAR) SHOULD be able to have configuration knob to configure itself in Mixed-Mode where it will support both efficiency-aware hosts and legacy hosts. However even in mixed-mode the router should check for duplicate entries in the NCE before creating a new ones and it should rate-limit creating new NCE based on requests from the same host MAC address.

The RECOMMENDED default mode of operation for the efficiency-aware router is Mixed-mode. Though it cannot reap the full benefit of efficiency related optimization described in this document.

10.2. Movement Detection

When a host moves from one subnet to another its IPv6 prefix changes and the movement detection is determined according to the existing IPv6 movement detection described in [DNA].

However, if the movement happens across different default routers in the subnet and the node likes to register with one of the default routers closest to its present location, it MUST send another registration request to the new default router. The new default router then first sends a NS to its peers with a link scope multicast message to IPv6 address ff02::2 with the ARO option.

10.2.1. Registration ownership

The subnet-local-routers check their respective NCE table for the particular registration. If the registration entry exists, the NEAR default router then calculates the 'age' of the registration by

subtracting the present time from the registration received time recorded at the NCE. The NEAR router then responds with a NA with ARO option Status being equal to 3 and replaces the 'registration lifetime' field with the 'age' of registration. Upon receiving the NA from the neighboring routers the prospective default router determines its registration ownership. If the other router registration age is higher than its own registration age, then the current router is considered to have the most recent registration ownership.

If both routers registration age are zero or within a 50msec window, then the TID field is used to determine the ownership. The higher value of TID wins. Note that the registration ownership and local movement detection behavior in NEAR router MUST be optionally configured. The NEAR routers MAY implement this feature. Configuring this option is needed when the NEAR routers are used in a low power and lossy network environment.

11. NCE Management in efficiency-aware Routers

The use of explicit registrations with lifetimes plus the desire to not multicast Neighbor Solicitation messages for hosts imply that we manage the Neighbor Cache entries slightly differently than in [ND]. This results in two different types of NCEs and the types specify how those entries can be removed:

Legacy: Entries that are subject to the normal rules in [ND] that allow for garbage collection when low on memory. Legacy entries are created only when there is no duplicate NCE. In mixed-mode and efficiency-aware mode the legacy entries are converted to the registered entries upon successful processing of ARO. Legacy type can be considered as union of garbage-collectible and Tentative Type NCEs described in [6LOWPAN-ND].

Registered: Entries that have an explicit registered lifetime and are kept until this lifetime expires or they are explicitly unregistered.

Note that the type of the NCE is orthogonal to the states specified in [ND].

When a host interacts with a router by sending Router Solicitations that does not match with the existing NCE entry of any type, a Legacy NCE is first created. Once a node successfully registers with a Router the result is a Registered NCE. As Routers send RAs to legacy

hosts, or receive multicast NS messages from other Routers the result is Legacy NCEs. There can only be one kind of NCE for an IP address at a time.

A Router Solicitation might be received from a host that has not yet registered its address with the router or from a legacy[ND] host in the Mixed-mode of operation.

In the 'Efficiency-aware' only mode the router MUST NOT modify an existing Neighbor Cache entry based on the SLLA option from the Router Solicitation. Thus, a router SHOULD create a tentative Legacy Neighbor Cache entry based on SLLA option when there is no match with the existing NCE. Such a legacy Neighbor Cache entry SHOULD be timed out in TENTATIVE_LEGACY_NCE_LIFETIME seconds unless a registration converts it into a Registered NCE.

However, in 'Mixed-mode' operation, the router does not require to keep track of TENTATIVE_LEGACY_NCE_LIFETIME as it does not know if the RS request is from a legacy host or the efficiency-aware hosts. However, it creates the legacy type of NCE and updates it to a registered NCE if the ARO NS request arrives corresponding to the legacy NCE. Successful processing of ARO will complete the NCE creation phase.

If ARO did not result in a duplicate address being detected, and the registration life-time is non-zero, the router creates and updates the registered NCE for the IPv6 address. If the Neighbor Cache is full and new entries need to be created, then the router SHOULD respond with a NA with status field set to 2. For successful creation of NCE, the router SHOULD include a copy of ARO and send NA to the requestor with the status field 0. A TLLA(Target Link Layer) Option is not required with this NA.

Typically for efficiency-aware routers (NEAR), the registration life-time and EUI-64 are recorded in the Neighbor Cache Entry along with the existing information described in [ND]. The registered NCE are meant to be ready and reachable for communication and no address resolution is required in the link. The efficiency-aware hosts will renew their registration to keep maintain the state of reachability of the NCE at the router. However the router may do NUD to the idle or unreachable hosts as per [ND].

In addition, NEAR default routers MUST associate a record of the age of the registration. 'Age' is a simple way to detect movement of a node from local default router to another. 'Age' information SHOULD contain System-time when the registration is first created or last refreshed. This system-time is deducted from the current system-time to determine the "age" of the registration and it is used for age

reporting with Neighbor advertisement for selection of registration ownership among the default-router contenders in case of local movement of the host from one default-router to another in the same subnet. 'Age' is always considered zero for a fresh registration or a registration refresh message.

11.1. Handling ND DOS Attack

IETF community has discussed possible issues with /64 DOS attacks on the ND networks when an attacker host can send thousands of packets to the router with an on-link destination address or sending RS messages to initiate a Neighbor Solicitation from the neighboring router which will create a number of INCOMPLETE NCE entries for non-existent nodes in the network resulting in table overflow and denial of service of the existing communications.

The efficiency-aware behavior documented in this specification avoids the ND DOS attacks by:

- Having the hosts register with the default router
- Having the hosts send their packets via the default router
- Not resolving addresses for the Routing Solicitor by mandating SLLA option along with RS
- Checking for duplicates in NCE before the registration
- Checking against the MAC-address and EUI-64 id is possible now for NCE matches
- On-link IPv6-destinations on a particular link must be registered else these packets are not resolved and extra NCEs are not created

It is RECOMMENDED that Mixed-mode operation and legacy hosts SHOULD NOT be mixed in the IPv6 link in order to avoid the ND DOS attacks. For the general case of Mixed-mode the router does not create INCOMPLETE NCEs for the registered hosts, but it follows the [ND] steps of NCE states for legacy hosts.

12. Mixed-Mode Operations

Mixed-Mode operation discusses the protocol behavior where the IPv6 subnet is composed with legacy IPv6 Neighbor Discovery compliant nodes and efficiency-aware IPv6 nodes implementing this specification.

The mixed-mode model SHOULD support the following configurations in the IPv6 link:

- The legacy IPv6 hosts and efficiency-aware-hosts in the network and a NEAR router

- o legacy IPv6 default-router and efficiency-aware hosts(EAH) in the link
- o one router is in mixed mode and the link contains both legacy IPv6 hosts and EAH
- o A link contains both efficiency-aware IPv6 router and hosts and legacy IPv6 routers and hosts and each host should be able to communicate with each other.

In mixed-mode operation, a NEAR MUST be configured for mixed-mode in order to support the legacy IPv6 hosts in the network. In mixed-mode, the NEAR MUST act as proxy for Neighbor Solicitation for DAD and Address Resolution on behalf of its registered hosts on that link. It should follow the NCE management for the EAH as described in this document and follow RFC 4861 NCE management for the legacy IPv6 hosts. Both in mixed-mode and efficiency-aware mode, the NEAR sets E-bit flag in the RA and does not set 'L' on-link bit.

If a NEAR receives NS message from the same host one with ARO and another without ARO then the NS message with ARO gets the precedence.

An efficiency-aware Host implementation SHOULD support falling back to legacy IPv6 node behavior when no efficiency-aware routers are available in the network during the startup. If the EAH was operational in efficiency-aware mode and it determines that the NEAR is no longer available, then it should send a RS and find an alternate default router in the link. If no efficiency-aware router is indicated from the RA, then the EAH SHOULD fall back into RFC 4861 behavior. On the other hand, in the efficiency-aware mode EAH SHOULD ignore multicast Router Advertisements(RA) sent by the legacy and Mixed-mode routers in the link.

In mixed mode operation, the Router SHOULD be able to do local movement detection based on ARO if it is configured for that operation for EAH hosts. For the legacy hosts, the mixed-mode router MAY follow classical IPv6 methods of movement detection and MAY act as ND proxy by sending NA with 'O' bit.[Reference??]

The routers that are running on efficiency-aware mode or legacy mode SHOULD NOT dynamically switch the mode without flushing the Neighbor Cache Entries.

In mixed mode, the NEAR SHOULD have a configurable interval for periodic unsolicited router advertisements based on the media type.

13. Bootstrapping

The bootstrapping mechanism described here is applicable for the

efficiency-aware hosts and routers. At the start, the host uses its link-local address to send Router Solicitation and then it sends the Node Registration message as described in this document in order to form the address. The Duplicate address detection process should be skipped if the network is guaranteed to have unique interface identifiers which is used to form an IPv6 address.

```
   Node                                                     Router

0.  |[Forms LL IPv6 addr]                                     |

1.  |       ---------- Router Solicitation -------->          |

    |                    [SLLAO]                              |

2.  |       <-------- Router Advertisement ---------          |

    |                    [PIO + SLLAO]                        |
    |                                                         |

3.  |       ----- Address Registration (NS) -------->         |

    |                    [ARO + SLLAO]                        |

4.  |       <-------- Neighbor Advertisement -------          |

    |                   [ARO with Status code]                |

5. ====> Address Assignment Complete
```

Figure 1: Neighbor Discovery Address Registration and bootstrapping

In the mixed mode operation, it is expected that logically there will be at least one legacy IPv6 router and another NEAR router present in the link. The legacy IPv6 router will follow RFC 4861 behavior and NEAR router will follow the efficiency-aware behavior for registration, NCE maintenance, forwarding packets from a EAH and it will also act as a ND proxy for the legacy IPv6 hosts querying to resolve a EAH node.

A legacy IPv6 host and EAH are not expected to see a difference in their bootstrapping if both legacy and efficiency-aware functionalities of rotuers are available in the network. It is RECOMMENDED that the EAH implementation SHOULD be able to behave like a legacy IPv6 host if it discovers that no efficiency-aware routing support is present in the link.

14. Handling Sleepy Nodes

The solution allows the sleepy nodes to complete its sleep schedule without waking up due to periodic Router Advertisement messages or due to Multicast Neighbor Solicitation for address resolution. The node registration lifetime SHOULD be synchronized with its sleep interval period in order to avoid waking up in the middle of sleep for registration refresh. Depending on the application, the registration lifetime SHOULD be equal to or integral multiple of a node's sleep interval period.

15. Duplicate Address Detection

In efficiency-aware mode, there is no need for Duplicate Address Detection(DAD) assuming that the deployment ensures unique 64bit identification availability for each registered host. In the event of collision of EUI64 field of ARO by two registration requests, the later request is denied if the first one is a valid request. The denied EAH node SHOULD pick another alternative IPv6 address to register to prevent further registration denial. The method of assignment of alternate IPv6 address is out of scope of this document.

In some networks there are multiple default routers and the registering node may move from one default router (where it was registered before) to another default router in the same subnet. Thus in order to differentiate between the duplicate request and the movement, the router checks the 64-bit MAC address and 'age' of the request. If there is an entry in the node already with 0 < 'age' < registration-life-time and the TID field of the existing entry and the new request is same with TID of the new request, it is a duplicate.

If the default router does not have a registered entry for this host, it should check whether it is a local movement. Please see 'Mobility Consideration section' for details.

16. Mobility Considerations

If the hosts move from one subnet to another, they MUST first de-register and then register themselves in the new subnet or network. If a node moves away without de-registration and returns to the network before the registration lifetime expires, its registration is still considered valid. For run-away nodes the registration expires after the lifetime expiry or due to unreachablity whichever comes first. Otherwise, the regular IPv6 Mobility [IPV6M]behavior applies.

In the multiple default router scenario, a node may move from its current primary default router to a prospective primary default router. At this point, the default routers use Neighbor Advertisements(NA) to arbitrate the latest ownership of the registration of host. The ownership of registration is useful for the Border Routers if they participate in a routing protocol which advertises proximity preferences or adjusts its own forwarding preference based on the host registration. This kind of forwarding or routing mechanisms are useful for energy efficiency and performance of the networks. See 'Movement Detection' section for details.

17. Other Considerations

17.1. Detecting Network Attachment(DNA)

IPv6 DNA[DNA] uses unicast ND probes and link-layer indications to detect movement of its network attachments. Upon detecting link-layer indication, it sends a all-routers Solicitation message. When the node implements this document along with DNA, it MUST send ARO option with its Neighbor Solicitation unicast message if the candidate router advertisement indicates that the router is a NEAR router. If the candiate router is a legacy router then and it is the only choice then the EAH host SHOULD adapt to the legacy behavior. However if EAH node implements DNA host capability as well, then it SHOULD give preference to the NEAR routers in its candidate list of routers.

Thus the ND optimization solution will work seamlessly with DNA implementations and no change is required in DNA solution because of Neighbor Discovery updates. It is a deployment and configuration consideration as to run the network in mixed mode or efficient-mode.

17.2. Proxying for Efficiency-Aware hosts

The efficient-ND SHOULD continue to support the legacy IPv6 Neighbor Solicitation requests in the mixed mode. The NEAR router SHOULD act as the ND proxy on behalf of EAH hosts for the legacy nodes' NS requests for EAH.

In the context of this specification, proxy ND means: defending a registered address over the backbone using NA messages with and ARO option and the Override bit set if the ARO option in the NS indicates either a different node (different EUI-64) or a older registration (when comparing the TID).

- o advertising a registered address over the backbone using NA messages, asynchronously or as a response to a Neighbor Solicitation messages.
- o Looking up a destination over the backbone in order to deliver packets arriving from the EAH host using Neighbor Solicitation messages.
- o Forwarding packets from the EAH over the backbone, and the other way around at a time if the devide has known sleeping periods or resides on a different link such as an LLN attached to the backbone.

Eventually triggering a look-up for a destination EAH that would not be registered at a given point of time, or as a verification of a registration.

17.3. DHCPv6 Interaction

Co-existence with DHCP: For classical IPv6, if DHCPv6 or central address allocation mechanism is used, then Neighbor Discovery autoconfiguration is not used for global address allocation. However, link-local duplicate address detection, Neighbor solicitation, Neighbor unreachability detection are still used. Upon assignment of the IPv6-address from DHCPv6, a EAH node SHOULD then register the IP-address with the default router for avoiding Duplicate address detection and Address Resolution. For Legacy DHCPv6 nodes there is no change in behavior. NOTE: DHCPv6 Server MUST be notified by NEAR for its efficiency-aware service interfaces. DHCPv6 server then SHOULD inform the DHCP requestor node about the default-rotuer capability during the address assignment period.

Although the solution described in this document prevents unnecesary multicast messages in the IPv6 ND procedure, it does not affect normal IPv6 multicast packets and ability of nodes to join and leave the multicast group or forwarding multicast traffic or responding to multicast queries.

18. RPL Implications

RPL [RFC6550] does not provide means for duplicate address detection and in particular does not have a concept of unique identifier. On the other hand, RPL is designed to discover and resolve conflicts that arise when a mobile device changes its point of attachment, with a sequence counter that is owned by the device and incremented at each new registration, called a DAOSequence. As we extend 6LoWPAN ND operation over a backbone and scale, there is a similar need to resolve the latest point of attachment of a device, whether this device moves at layer 2 over a WIFI infrastructure, or at layer 3 within a RPL DODAG or from a DODAG to another one attached to the

same backbone. In order to cover all cases in a consistent fashion, this document requires that a sequence counter call TID for Transaction ID and with the similar rules as the RPL DAOSequence is added to the ND registration. This document defines the TID operations and RPL may use the reserved fields for their purpose inside the LLN.

19. Updated Neighbor Discovery Constants

This section discusses the updated default values of ND constants based on [ND] section 10. New and changed constants are listed only for efficiency-aware-nd implementation. These values SHOULD be configurable and tunable to fit implementations and deployment.

```
Router Constants:
MAX_RTR_ADVERTISEMENTS(NEW)             3 transmissions
MIN_DELAY_BETWEEN_RAS(CHANGED)          1 second
TENTATIVE_LEGACY_NCE_LIFETIME(NEW)      30 seconds

Host Constants:
MAX_RTR_SOLICITATION_INTERVAL(NEW)      60 seconds
```

Also refer to [ENH-ND] , [IMPAT-ND] and [6LOWPAN-ND] for further tuning of ND constants.

20. Security Considerations

These optimizations are not known to introduce any new threats against Neighbor Discovery beyond what is already documented for IPv6 [RFC 3756].

Section 11.2 of [ND] applies to this document as well.

This mechanism minimizes the possibility of ND /64 DOS attacks in efficiency-aware mode. See Section 11.1.

21. IANA Considerations

A new flag (E-bit) in RA has been introduced. IANA assignment of the E-bit flag is required upon approval of this document.

22. Changelog

Changes from draft-chakrabarti-nordmark-energy-aware-nd-02:

- o Added clarification that SLLA is not required for ARO in a point-to-point link
- o Clarified that the document is indeed an optimization for legacy IPv6 ND
- o Adressed editorial comments and fixed typoes. Some more editorial work is needed
- o Added another usecase for Z-Wave example. Clarified 3GPP Networks related comments on existing ND optimizations.

23. Acknowledgements

The primary idea of this document are from 6LoWPAN Neighbor Discovery document [6LOWPAN-ND] and the discussions from the 6lowpan working group members, chairs Carsten Bormann and Geoff Mulligan and through our discussions with Zach Shelby, editor of the [6LOWPAN-ND].

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Appendix A. Usecase Analysis

This section provides applicability scenarios where the efficiency-aware Neighbor Discovery will be most beneficial. Most likely the usecases will be detailed in a separate document.

A.1. Data Center Routers on the link

Efficiency-aware Routers and hosts are useful in IPv6 networks in the Data Center as they produce less signaling and also provides ways to minimize the ND flood of messages. Moreover, this mechanism will work with data-center nodes which are deliberately in sleep mode for saving energy.

This solution will work well in Data Center Virtual network and VM scenarios where number of VLANs are very high and ND signalings are undesirably high due the multicast messaging and periodic Router Advertisments and Neighbor Unreachability detections.

A.2. Edge Routers and Home Networks

An Edge Router in the network will also benefit implementing the efficiency-aware Neighbor Discovery behavior in order to save the signaling and keeping track of the registered nodes in its domain. A

BNG sits at the operator's edge network and often the BNG has to handle a large number of home CPEs. If a BNG runs Neighbor Discovery protocol and acts as the default router for the CPE at home, this solution will be helpful for reducing the control messages and improving network performances.

The same solution can be run on CPE or Home Residential Gateways to assign IPv6 addresses to the wired and wireless home devices without the problem of ND flooding issues and consuming less power. It provides mechanism for the sleepy nodes to adjust their registration lifetime according to their sleep schedules.

A.3. M2M Networks

Any Machine-to-machine(M2M) networks such as IPv6 surveilance networks, wireless monitoring networks and other m2m networks desire for efficiency-aware control protocols and dynamic address allocation. The in-built address allocation and autoconfiguration mechanism in IPv6 along with the default router capability will be useful for the simple small-scale networks without having the burden of DHCPv6 service and Routing Protocols.

A.4. Wi-fi Networks

In Wi-fi networks, a multicast message will consume the wireless link on all Access Points around a switched fabric and will be transmitted at the lowest speed possible in order to ensure the maximum reception by all wireless nodes. This means that in an environment where bandwidth is scarce, a single multicast packet may consume the bandwidth for hundreds of unicast packets.

The Wi-fi IPv6 hosts can act as efficiency-aware hosts and register with their nearest default router with NEAR behavior. This method reduces multicast operations in the wireless access points or routers by using this optimization.

A.5. 3GPP Networks

Section 9.2.1.1 of TS23.060 allows periodic RA and TS 123.401 stays silent about periodic RA while 3GPP TS29.061 recommends large values for minimum and maximum periodic router advertisements for reduced periodic mesages. Though RFC6459 describes best practices about IPv6 3GPP systems behavior, this ND optimization standard specification will be a helpful reference for 3GPP documents. LTE terminals (cell phones) may also benefit with reduced multicast messages described in this document in the wireless mode.

A.6. Industrial Networks

RPL [RFC6550] is used for Industrial wireless networks.

A.7. Set and forget offline network

Home control modules designed for networked environments may be deployed in very simple settings like garden path lighting controlled by wireless light and motion sensors. Once the network has been created and sensors have been associated with the light modules, the installer takes away the configuration tool which was used to set up the network. Most likely a ULA prefix is used, since multiple hops may be needed. None of the sensors and light modules has the capability of handing out fresh prefixes. Thus, for a set-and-forget style off-line network to work, the nodes must be provided an infinite prefix lifetime since they have nowhere to ask for a fresh one.

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