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Address Resolution Problems in Large Data Center Networks
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Abstract

This document examines address resolution issues related to the scaling of data centers with a very large numbers of hosts. The initial scope is relatively narrow. Specifically, it focuses on address resolution (ARP and ND) within the data center.

Status of this Memo

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1. Introduction

This document examines issues related to the large scaling of data centers. Specifically, this document focuses on address resolution (ARP in IPv4 and Neighbor Discovery in IPv6) within the data center. Although strictly speaking the scope of address resolution is confined to a single L2 broadcast domain (i.e., ARP runs at the L2 layer below IP), the issue is complicated by routers having many interfaces on which address resolution must be performed or with the presence of IEEE 802.1Q domains, where individual VLANs effectively form their own L2 broadcast domains. Thus, the scope of address resolution spans both the L2 link and the devices attached to those links.

This document identifies potential issues associated with address resolution in data centers with a large number of hosts. The scope of this document is intentionally relatively narrow as it mirrors the ARMD WG charter. This document lists "pain points" that are being experienced in current data centers. The goal of this document is to focus on address resolution issues and not other broader issues that might arise in data centers.

2. Terminology

Address Resolution: the process of determining the link-layer address corresponding to a given IP address. In IPv4, address resolution is performed by ARP [RFC0826]; in IPv6, it is provided by Neighbor Discovery (ND) [RFC4861].

Application: software that runs on either a physical or virtual machine, providing a service (e.g., web server, database server, etc.)

L2 Broadcast Domain: The set of all links, repeaters, and switches that are traversed to reach all nodes that are members of a given L2 broadcast domain. In IEEE 802.1Q networks, a broadcast domain corresponds to a single VLAN.

Host (or server): A computer system on the network.

Hypervisor: Software running on a host that allows multiple VMs to run on the same host.

Virtual machine (VM): A software implementation of a physical machine that runs programs as if they were executing on a physical, non-virtualized machine. Applications (generally) do not know they are running on a VM as opposed to running on a

"bare" host or server, though some systems provide a paravirtualization environment that allows an operating systems or application to be aware of the presences of virtualization for optimization purposes.

ToR: Top of Rack Switch. A switch placed in a single rack to aggregate network connectivity to and from hosts in that rack.

EoR: End of Row Switch. A switch used to aggregate network connectivity from multiple racks. EoR switches are the next level of switching above ToR switches.

3. Background

Large, flat L2 networks have long been known to have scaling problems. As the size of an L2 broadcast domain increases, the level of broadcast traffic from protocols like ARP increases. Large amounts of broadcast traffic pose a particular burden because every device (switch, host and router) must process and possibly act on such traffic. In extreme cases, "broadcast storms" can occur where the quantity of broadcast traffic reaches a level that effectively brings down part or all of a network. For example, poor implementations of loop detection and prevention or misconfiguration errors can create conditions that lead to broadcast storms as network conditions change. The conventional wisdom for addressing such problems has been to say "don't do that". That is, split large L2 networks into multiple smaller L2 networks, each operating as its own L3/IP subnet. Numerous data center networks have been designed with this principle, e.g., with each rack placed within its own L3 IP subnet. By doing so, the broadcast domain (and address resolution) is confined to one Top of Rack switch, which works well from a scaling perspective. Unfortunately, this conflicts in some ways with the current trend towards dynamic work load shifting in data centers and increased virtualization as discussed below.

Workload placement has become a challenging task within data centers. Ideally, it is desirable to be able to dynamically reassign workloads within a data center in order to optimize server utilization, add additional servers in response to increased demand, etc. However, servers are often pre-configured to run with a given set of IP addresses. Placement of such servers is then subject to constraints of the IP addressing restrictions of the data center. For example, servers configured with addresses from a particular subnet could only be placed where they connect to the IP subnet corresponding to their IP addresses. If each top of rack switch is acting as a gateway for its own subnet, a server can only be connected to the one top of rack switch. This gateway switch represents the L2/L3 boundary. A

similar constraint occurs in virtualized environments, as discussed next.

Server virtualization is fast becoming the norm in data centers. With server virtualization, each physical server supports multiple virtual machines, each running its own operating system, middleware and applications. Virtualization is a key enabler of workload agility, i.e., allowing any server to host any application (on its own VM) and providing the flexibility of adding, shrinking, or moving VMs within the physical infrastructure. Server virtualization provides numerous benefits, including higher utilization, increased data security, reduced user downtime, and even significant power conservation, along with the promise of a more flexible and dynamic computing environment.

The discussion below focuses on VM placement and migration. Keep in mind, however, that even in a non-virtualized environment, many of the same issues apply to individual workloads running on standalone machines. For example, when increasing the number of servers running a particular workload to meet demand, placement of those workloads may be constrained by IP subnet numbering considerations, as discussed earlier.

The greatest flexibility in VM and workload management occurs when it is possible to place a VM (or workload) anywhere in the data center regardless of what IP addresses the VM uses and how the physical network is laid out. In practice, movement of VMs within a data center is easiest when VM placement and movement does not conflict with the IP subnet boundaries of the data center's network, so that the VM's IP address need not be changed to reflect its actual point of attachment on the network from an L3/IP perspective. In contrast, if a VM moves to a new IP subnet, its address must change, and clients will need to be made aware of that change. From a VM management perspective, management is simplified if all servers are on a single large L2 network.

With virtualization, it is not uncommon to have a single physical server host ten (or more) VMs, each having its own IP (and MAC) addresses. Consequently, the number of addresses per machine (and hence per subnet) is increasing, even when the number of physical machines stays constant. In a few years, the numbers will likely be even higher.

In the past, applications were static in the sense that they tended to stay in one physical place. An application installed on a physical machine would stay on that machine because the cost of moving an application elsewhere was generally high. Moreover, physical servers hosting applications would tend to be placed in such

a way as to facilitate communication locality. That is, applications running on servers would be physically located near the servers hosting the applications they communicated with most heavily. The network traffic patterns in such environments could thus be optimized, in some cases keeping significant traffic local to one network segment. In these more static and carefully managed environments, it was possible to build networks that approached scaling limitations, but did not actually cross the threshold.

Today, with the proliferation of VMs, traffic patterns are becoming more diverse and less predictable. In particular, there can easily be less locality of network traffic as VMs hosting applications are moved for such reasons as reducing overall power usage (by consolidating VMs and powering off idle machine) or to move a VM to a physical server with more capacity or a lower load. In today's changing environments, it is becoming more difficult to engineer networks as traffic patterns continually shift as VMs move around.

In summary, both the size and density of L2 networks is increasing. In addition, increasingly dynamic workloads and the increased usage of VMs is creating pressure for ever larger L2 networks. Today, there are already data centers with over 100,000 physical machines and many times that number of VMs. This number will only increase going forward. In addition, traffic patterns within a data center are also constantly changing. Ultimately, the issues described in this document might be observed at any scale depending on the particular design of the data center.

4. Address Resolution in IPv4

In IPv4 over Ethernet, ARP provides the function of address resolution. To determine the link-layer address of a given IP address, a node broadcasts an ARP Request. The request is delivered to all portions of the L2 network, and the node with the requested IP address replies with an ARP Reply. ARP is an old protocol, and by current standards, is sparsely documented. For example, there are no clear requirement for retransmitting ARP Requests in the absence of replies. Consequently, implementations vary in the details of what they actually implement [RFC0826][RFC1122].

From a scaling perspective, there are a number of problems with ARP. First, it uses broadcast, and any network with a large number of attached hosts will see a correspondingly large amount of broadcast ARP traffic. The second problem is that it is not feasible to change host implementations of ARP - current implementations are too widely entrenched, and any changes to host implementations of ARP would take years to become sufficiently deployed to matter. That said, it may

be possible to change ARP implementations in hypervisors, L2/L3 boundary routers, and/or ToR access switches, to leverage such techniques as Proxy ARP. Finally, ARP implementations need to take steps to flush out stale or otherwise invalid entries. Unfortunately, existing standards do not provide clear implementation guidelines for how to do this. Consequently, implementations vary significantly, and some implementations are "chatty" in that they just periodically flush caches every few minutes and send new ARP queries.

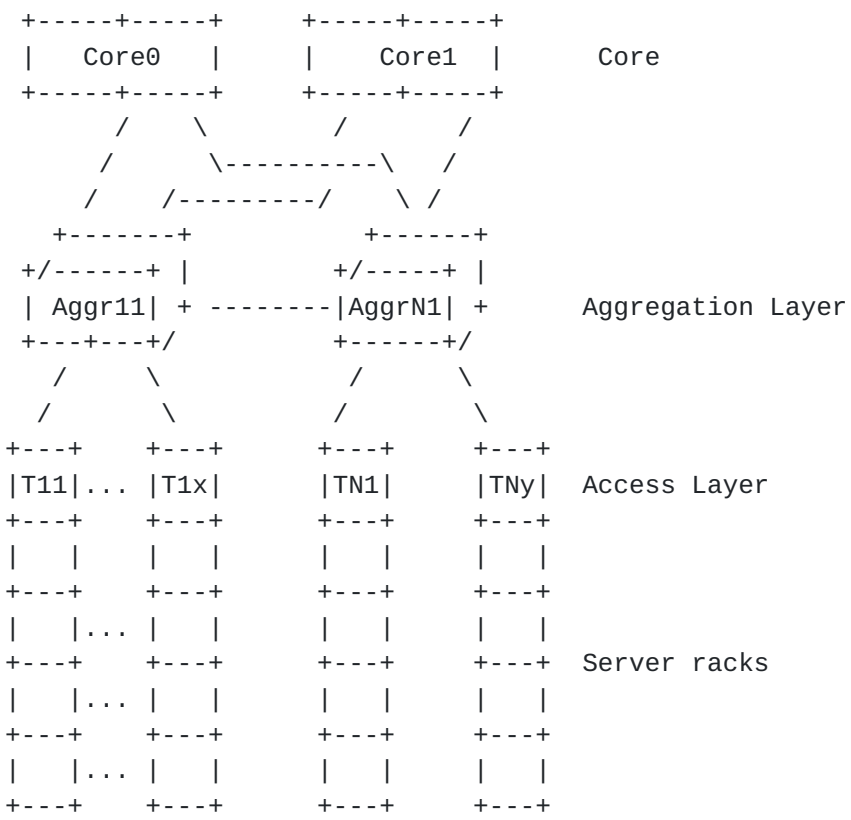
5. Address Resolution in IPv6

Broadly speaking, from the perspective of address resolution, IPv6's Neighbor Discovery (ND) behaves much like ARP, with a few notable differences. First, ARP uses broadcast, whereas ND uses multicast. Specifically, when querying for a target IP address, ND maps the target address into an IPv6 Solicited Node multicast address. Using multicast rather than broadcast has the benefit that the multicast frames do not necessarily need to be sent to all parts of the network, i.e., only to segments where listeners for the Solicited Node multicast address reside. In the case where multicast frames are delivered to all parts of the network, sending to a multicast still has the advantage that most (if not all) nodes will filter out the (unwanted) multicast query via filters installed in the NIC rather than burdening host software with the need to process such packets. Thus, whereas all nodes must process every ARP query, ND queries are processed only by the nodes to which they are intended. In cases where multicast filtering can't effectively be implemented in the NIC (e.g., as on hypervisors supporting virtualization), filtering would need to be done in software (e.g., in the hypervisor's vSwitch).

6. Generalized Data Center Design

There are many different ways in which data center networks might be designed. The designs are usually engineered to suit the particular workloads that are being deployed in the data center. For example, a large web server farm might be engineered in a very different way than a general-purpose multi-tenant cloud hosting service. However in most cases the designs can be abstracted into a typical three-layer model consisting of an access layer, an aggregation layer and the Core. The access layer generally refers to the switches that are closest to the physical or virtual severs, the aggregation layer serves to interconnect multiple access layer devices. The Core switches connect the aggregation switches to the larger network core. Figure 1 shows a generalized data center design, which captures the

essential elements of various alternatives.



Typical Layered Architecture in DC

Figure 1

6.1. Access Layer

The access switches provide connectivity directly to/from physical and virtual servers. The access layer may be implemented by wiring the servers within a rack to a top-of-rack (ToR) switch or, less commonly, the servers could be wired directly to an end-of-row (EoR) switch. A server rack may have a single uplink to one access switch, or may have dual uplinks to two different access switches.

6.2. Aggregation Layer

In a typical data center, aggregation switches interconnect many ToR switches. Usually there are multiple parallel aggregation switches, serving the same group of ToRs to achieve load sharing. It is no longer uncommon to see aggregation switches interconnecting hundreds of ToR switches in large data centers.

6.3. Core

Core switches connect multiple aggregation switches and interface with data center gateway(s) to external networks or interconnect to different sets of racks within one data center.

6.4. L3 / L2 Topological Variations

6.4.1. L3 to Access Switches

In this scenario the L3 domain is extended all the way to the access switches. Each rack enclosure consists of a single L2 domain, which is confined to the rack. In general, there are no significant ARP/ND scaling issues in this scenario as the L2 domain cannot grow very large. This topology has benefits in scenarios where servers attached to a particular access switch generally run VMs that are confined to using a single subnet. These VMs and the applications they host aren't moved (migrated) to other racks which might be attached to different access switches (and different IP subnets). A small server farm or very static compute cluster might be best served via this design.

6.4.2. L3 to Aggregation Switches

When the L3 domain only extends to aggregation switches, hosts in any of the IP subnets configured on the aggregation switches can be reachable via L2 through any access switches if access switches enable all the VLANs. This topology allows a greater level of flexibility as servers attached to any access switch can be reloaded with VMs that have been provisioned with IP addresses from multiple prefixes as needed. Further, in such an environment, VMs can migrate between racks without IP address changes. The drawback of this design however is that multiple VLANs have to be enabled on all access switches and all access-facing ports on aggregation switches. Even though L2 traffic is still partitioned by VLANs, the fact that all VLANs are enabled on all ports can lead to broadcast traffic on all VLANs to traverse all links and ports, which is same effect as one big L2 domain on the access-facing side of the aggregation switch. In addition, internal traffic itself might have to cross different L2 boundaries resulting in significant ARP/ND load at the aggregation switches. This design provides a good tradeoff between flexibility and L2 domain size. A moderate sized data center might utilize this approach to provide high availability services at a single location.

6.4.3. L3 in the Core only

In some cases where a wider range of VM mobility is desired (i.e. greater number of racks among which VMs can move without IP address change), the L3 routed domain might be terminated at the core routers themselves. In this case VLANs can span across multiple groups of aggregation switches, which allow hosts to be moved among more number of server racks without IP address change. This scenario results in the largest ARP/ND performance impact as explained later. A data center with very rapid workload shifting may consider this kind of design.

6.4.4. Overlays

There are several approaches where overlay networks can be used to build very large L2 networks to enable VM mobility. Overlay networks using various L2 or L3 mechanisms allow interior switches/routers to mask host addresses. In addition, L3 overlays can help the data center designer control the size of the L2 domain and also enhance the ability to provide multi tenancy in data center networks. However, the use of overlays does not eliminate traffic associated with address resolution, it simply moves it to regular data traffic. That is, address resolution is implemented in the overlay, and is not directly visible to the switches of the DC network.

A potential problem that arises in a large data center is when a large number of hosts communicate with their peers in different subnets, all these hosts send (and receive) data packets to their respective L2/L3 boundary nodes as the traffic flows are generally bi-directional. This has the potential to further highlight any scaling problems. These L2/L3 boundary nodes have to process ARP/ND requests sent from originating subnets and resolve physical (MAC) addresses in the target subnets for what are generally bi-directional flows. Therefore, for maximum flexibility in managing the data center workload, it is often desirable to use overlays to place related groups of hosts in the same topological subnet to avoid the L2/L3 boundary translation. The use of overlays in the data center network can be a useful design mechanism to help manage a potential bottleneck at the L2 / L3 boundary by redefining where that boundary exists.

6.5. Factors that Affect Data Center Design

6.5.1. Traffic Patterns

Expected traffic patterns play an important role in designing the appropriately sized access, aggregation and core networks. Traffic patterns also vary based on the expected use of the data center.

Broadly speaking it is desirable to keep as much traffic as possible on the access layer in order to minimize the bandwidth usage at the aggregation layer. If the expected use of the data center is to serve as a large web server farm, where thousands of nodes are doing similar things and the traffic pattern is largely in and out a large data center, an access layer with EoR switches might be used as it minimizes complexity, allows for servers and databases to be located in the same L2 domain and provides for maximum density.

A data center that is expected to host a multi-tenant cloud hosting service might have some completely unique requirements. In order to isolate inter-customer traffic smaller L2 domains might be preferred and though the size of the overall data center might be comparable to the previous example, the multi-tenant nature of the cloud hosting application requires a smaller more compartmentalized access layer. A multi-tenant environment might also require the use of L3 all the way to the access layer ToR switch.

Yet another example of a work load with a unique traffic pattern is a high performance compute cluster where most of the traffic is expected to stay within the cluster but at the same time there is a high degree of crosstalk between the nodes. This would once again call for a large access layer in order to minimize the requirements at the aggregation layer.

6.5.2. Virtualization

Using virtualization in the data center further serves to increase the possible densities that can be achieved. Virtualization also further complicates the requirements on the access layer as that determines the scope of server migrations or failover of servers on physical hardware failures.

Virtualization also can place additional requirements on the m aggregation switches in terms of address resolution table size and the scalability of any address learning protocols that might be used on those switches. The use of virtualization often also requires the use of additional VLANs for High Availability beaconing which would need to span across the entire virtualized infrastructure. This would require the access layer to span as wide as the virtualized infrastructure.

6.5.3. Summary

The designs described in this section have a number of tradeoffs. The L3 to access switches design described in Section 6.4.1 is the only design that constrains L2 domain size in a fashion that avoids ARP/ND scaling problems. However, that design has limitations and

does not address some of the other requirements that lead to configurations that make use of larger L2 domains. Consequently, ARP/ND scaling issues are a real problem in practice.

7. Problem Itemization

This section articulates some specific problems or "pain points" that are related to large data centers. It is a future activity to determine which of these areas can or will be addressed by ARMD or some other IETF WG.

7.1. ARP Processing on Routers

One pain point with large L2 broadcast domains is that the routers connected to the L2 domain may need to process a significant amount of ARP traffic in some cases. In particular, environments where the aggregate level of ARP traffic is very large may lead to a heavy ARP load on routers. Even though the vast majority of ARP traffic may well not be aimed at that router, the router still has to process enough of the ARP Request to determine whether it can safely be ignored. The ARP algorithm specifies that a recipient must update its ARP cache if it receives an ARP query from a source for which it has an entry [RFC0826].

ARP processing in routers is commonly handled in a "slow path" software processor rather than directly by a hardware ASIC as is the case when forwarding packets. Such a design significantly limits the rate at which ARP traffic can be processed compared to the rate at which ASICs can forward traffic. Current implementations at the time of this writing can support ARP processing in the low thousands of ARP packets per second. In some deployments, limitations on the rate of ARP processing have been cited as being a problem.

To further reduce the ARP load, some routers have implemented additional optimizations in their forwarding ASIC paths. For example, some routers can be configured to discard ARP Requests for target addresses other than those assigned to the router. That way, the router's software processor only receives ARP Requests for addresses it owns and must respond to. This can significantly reduce the number of ARP Requests that must be processed by the router.

Another optimization concerns reducing the number of ARP queries targeted at routers, whether for address resolution or to validate existing cache entries. Some routers can be configured to broadcast periodic gratuitous ARPs [RFC5227]. Upon receipt of a gratuitous ARP, implementations mark the associated entry as "fresh", resetting the aging timer to its maximum setting. Consequently, sending out

periodic gratuitous ARPs can effectively prevent nodes from needing to send ARP Requests intended to revalidate stale entries for a router. The net result is an overall reduction in the number of ARP queries routers receive. Gratuitous ARPs, broadcast to all nodes in the L2 broadcast domain, may in some cases also pre-populate ARP caches on neighboring devices, further reducing ARP traffic. But it is not believed that pre-population of ARP entries is supported by most implementations, as the ARP specification [RFC0826] recommends only that pre-existing ARP entries be updated upon receipt of ARP messages; it does not call for the creation of new entries when when none already exist.

Finally, another area concerns the overhead of processing IP packets for which no ARP entry exists. Existing standards specify that one (or more) IP packets for which no ARP entry exists should be queued pending successful completion of the address resolution process [RFC1122] [RFC1812]. Once an ARP query has been resolved, any queued packets can be forwarded on. Again, the processing of such packets is handled in the "slow path", effectively limiting the rate at which a router can process ARP "cache misses" and is viewed as a problem in some deployments today. Additionally, if no response is received, the router may send the ARP/ND query multiple times. If no response is received after a number of ARP/ND requests, the router needs to drop any queued data packets, and may send an ICMP destination unreachable message as well [RFC0792]. This entire process can be CPU intensive.

Although address-resolution traffic remains local to one L2 network, some data center designs terminate L2 domains at individual aggregation switches/routers (e.g., see Section 4.4.2). Such routers can be connected to a large number of interfaces (e.g., 100 or more). While the address resolution traffic on any one interface may be manageable, the aggregate address resolution traffic across all interfaces can become problematic.

Another variant of the above issue has individual routers servicing a relatively small number of interfaces, with the individual interfaces themselves serving very large subnets. Once again, it is the aggregate quantity of ARP traffic seen across all of the router's interfaces that can be problematic. This "pain point" is essentially the same as the one discussed above, the only difference being whether a given number of hosts are spread across a few large IP subnets or many smaller ones.

When hosts in two different subnets under the same L2/L3 boundary router need to communicate with each other, the L2/L3 router not only has to initiate ARP/ND requests to the target's subnet, it also has to process the ARP/ND requests from the originating subnet. This

process further adds to the overall ARP processing load.

7.2. IPv6 Neighbor Discovery

Though IPv6's Neighbor Discovery behaves much like ARP there are several notable differences which result in a different set of potential issues. From an L2 perspective, an important difference is that ND address resolution requests are sent via multicast, which results in ND queries only being processed by the nodes for which they are intended. This reduces the total number of ND packets that an implementation will receive compared with broadcast ARPs.

Another key difference concerns revalidating stale ND entries. ND requires that nodes periodically re-validate any entries they are using, to ensure that bad entries are timed out quickly enough that TCP does not terminate a connection. Consequently, some implementations will send out "probe" ND queries to validate in-use ND entries as frequently as every 35 seconds [RFC4861]. Such probes are sent via unicast (unlike in the case of ARP). However, on larger networks, such probes can result in routers receiving many such queries (i.e., many more than with ARP, which does not specify such behavior). Unfortunately, the IPv4 mitigation technique of sending gratuitous ARPs (as described in section 7.1) does not work in IPv6. The ND specification specifically states that gratuitous ND "updates" cannot cause an ND entry to be marked "valid". Rather, such entries are marked "probe", which causes the receiving node to (eventually) generate a probe back to the sender, which in this case is precisely the behavior that the router is trying to prevent!

Routers implementing NUD (for neighboring destinations) will need to process neighbor cache state changes such as transitioning entries from REACHABLE to STALE. How this capability is implemented may impact the scalability of ND on a router. For example, one possible implementation is to have the forwarding operation detect when an ND entry is referenced that needs to transition from REACHABLE to STALE, by signaling an event that would need to be processed by the software processor. Such an implementation could increase the load on the service processor much in the same way that a high rate of ARP requests have led to problems on some routers.

It should be noted that ND does not require the sending of probes in all cases. Section 7.3.1 of [RFC4861] describes a technique whereby hints from TCP can be used to verify that an existing ND entry is working fine and does not need to be revalidated.

Finally, IPv6 and IPv4 are often run simultaneously and in parallel on the same network, i.e., in dual-stack mode. In such environments, the IPv4 and IPv6 issues enumerated above compound each other.

7.3. MAC Address Table Size Limitations in Switches

L2 switches maintain L2 MAC address forwarding tables for all sources and destinations traversing through the switch. These tables are populated through learning and are used to forward L2 frames to their correct destination. The larger the L2 domain, the larger the tables have to be. While in theory a switch only needs to keep track of addresses it is actively using (sometimes called "conversational learning"), switches flood broadcast frames (e.g., from ARP), multicast frames (e.g., from Neighbor Discovery) and unicast frames to unknown destinations. Switches add entries for the source addresses of such flooded frames to their forwarding tables. Consequently, MAC address table size can become a problem as the size of the L2 domain increases. The table size problem is made worse with VMs, where a single physical machine now hosts many VMs (in the 10's today, but growing rapidly as the number of cores per CPU increases), since each VM has its own MAC address that is visible to switches.

When L3 extends all the way to access switches (see Section 4.4.1), the size of MAC address tables in switches is not generally a problem. When L3 extends only to aggregation switches (see Section 4.4.2), however, MAC table size limitations can be a real issue.

8. Summary

This document has outlined a number of issues related to address resolution in large data centers. In particular this document has described different scenarios where such issues might arise, what these potential issues are, and along with outlining fundamental factors that cause them. It is hoped that describing specific pain points will facilitate a discussion as to whether and how to best address them.

9. Acknowledgments

This document has been significantly improved by comments from Manov Bhatia, David Black, Stewart Bryant, Ralph Droms, Linda Dunbar, Donald Eastlake, Wesley Eddy, Anoop Ghanwani, Sue Hares, Joel Halpurn, Pete Resnick, Benson Schliesser, T. Sridhar and Lucy Yong. Igor Gashinsky deserves additional credit for highlighting some of the ARP-related pain points and for clarifying the difference between what the standards require and what some router vendors have actually implemented in response to operator requests.

10. IANA Considerations

This document makes no request of IANA. [Note: this section should be removed upon final RFC publication.]

11. Security Considerations

This document does not create any security implications nor does it have any security implications. The security vulnerabilities in ARP are well known and this document does not change or mitigate them in any way. Security considerations for Neighbor Discovery are discussed in [RFC4861] and [RFC6583].

12. Change Log

12.1. Changes from -03 to -04

1. Numerous editorial changes in response to IESG reviews and Gen Art reviews from Joel Halpurn and Manav Bhatia.

12.2. Changes from -02 to -03

1. Wordsmithing and editorial improvements in response to comments from David Black, Donald Eastlake, Anoop Ghanwani, Benson Schliesser, T. Sridhar and Lucy Yong.

12.3. Changes from -01

1. Wordsmithing and editorial improvements.

12.4. Changes from -00

1. Merged draft-karir-armd-datacenter-reference-arch-00.txt into this document.

2. Added section explaining how ND differs from ARP and the implication on address resolution "pain".

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