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Analysis of the 64-bit Boundary in IPv6 Addressing
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Abstract

The IPv6 unicast addressing format includes a separation between the prefix used to route packets to a subnet and the interface identifier used to specify a given interface connected to that subnet. Historically the interface identifier has been defined as 64 bits long, leaving 64 bits for the prefix. This document discusses the reasons for this fixed boundary and the issues involved in treating it as a variable boundary.

Status of This Memo

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1. Introduction

IPv6 addresses were originally chosen to be 128 bits long to provide flexibility and new possibilities, rather than simply relieving the IPv4 address shortage by doubling the address size to 64 bits. The notion of a 64-bit boundary in the address was introduced after the initial design was done. There were two motivations for introducing it. One was the original "8+8" proposal [DRAFT-odell] that eventually led to ILNP [RFC6741], which required a fixed point for

the split between local and wide-area parts of the address. The other was the expectation that EUI-64 MAC addresses would become widespread in place of 48-bit addresses, coupled with the plan at that time that auto-configured addresses would normally be based on interface identifiers derived from MAC addresses.

The IPv6 addressing architecture [RFC4291] specifies that a unicast address is divided into n bits of subnet prefix followed by (128-n) bits of interface identifier (IID). Since IPv6 routing is entirely based on variable length subnet masks, there is no architectural assumption that n has any particular fixed value. However, RFC 4291 also describes a method of forming interface identifiers from IEEE EUI-64 hardware addresses [IEEE802] and this does specify that such interface identifiers are 64 bits long. Various other methods of forming interface identifiers also specify a length of 64 bits. This has therefore become the de facto length of almost all IPv6 interface identifiers. One exception is documented in [RFC6164], which standardises 127-bit prefixes for inter-router links.

Recently it has been clarified that the bits in an IPv6 interface identifier have no particular meaning and should be treated as opaque values [I-D.ietf-6man-ug]. Therefore, there are no bit positions in the currently used 64 bits that need to be preserved. The addressing architecture as modified by [I-D.ietf-6man-ug] now states that "For all unicast addresses, except those that start with the binary value 000, Interface IDs are required to be 64 bits long. If derived from an IEEE MAC-layer address, they must be constructed in Modified EUI-64 format."

The question is often asked why the boundary is set rigidly at /64. This limits the length of a routing prefix to 64 bits, whereas architecturally, and from the point of view of routing protocols, it could be anything (in theory) between /1 and /128 inclusive. Here, we only discuss the question of a shorter IID, allowing a longer routing prefix.

The purpose of this document is to analyse the issues around this question. We make no proposal for change, but we do analyse the possible effects of a change.

2. Scenarios for prefixes longer than /64

In this section we describe existing scenarios where prefixes longer than /64 have been used or proposed.

2.1. Insufficient address space delegated

A site may not be delegated a sufficiently large prefix from which to allocate a /64 prefix to all of its internal subnets. In this case the site may either determine that it does not have enough address space to number all its network elements and thus, at the very best, be only partially operational, or it may choose to use internal prefixes longer than /64 to allow multiple subnets and the hosts within them to be configured with addresses.

In this case, the site might choose, for example, to use a /80 per subnet, in combination with hosts using either manually configured addressing or DHCPv6.

Scenarios that have been suggested where an insufficient prefix might be delegated include home or small office networks, vehicles, building services and transportation services (road signs, etc.). It should be noted that the homenet architecture text [I-D.ietf-homenet-arch] states that a CPE should consider the lack of sufficient address space to be an error condition, rather than using prefixes longer than /64 internally.

Another scenario occasionally suggested is one where the Internet address registries actually begin to run out of IPv6 prefix space, such that operators can no longer assign reasonable prefixes to users in accordance with [RFC6177]. We mention this scenario here for completeness, and we briefly analyze it in Section 7.

2.2. Concerns over ND cache exhaustion

A site may be concerned that it is open to neighbour discovery (ND) cache exhaustion attacks, whereby an attacker sends a large number of messages in rapid succession to a series of (most likely inactive) host addresses within a specific subnet, in an attempt to fill a router's ND cache with ND requests pending completion, in so doing denying correct operation to active devices on the network.

An example would be to use a /120 prefix, limiting the number of addresses in the subnet to be similar to an IPv4 /24 prefix, which should not cause any concerns for ND cache exhaustion. Note that the prefix does need to be quite long for this scenario to be valid. The number of theoretically possible ND cache slots on the segment needs to be of the same order of magnitude as the actual number of hosts. Thus small increases from the /64 prefix length do not have a noticeable impact: even 2^32 potential entries, a factor of two billion decrease compared to 2^64, is still more than enough to exhaust the memory on current routers.

As in the previous scenario, hosts would likely be manually configured with addresses, or use DHCPv6.

It should be noted that several other mitigations of the ND cache attack are described in [RFC6583], and that limiting the size of the cache and the number of incomplete entries allowed would also defeat the attack.

3. Interaction with IPv6 specifications

The precise 64-bit length of the Interface ID is widely mentioned in numerous RFCs describing various aspects of IPv6. It is not straightforward to distinguish cases where this has normative impact or affects interoperability. This section aims to identify specifications that contain an explicit reference to the 64-bit size. Regardless of implementation issues, the RFCs themselves would all need to be updated if the 64-bit rule was changed, even if the updates were small.

First and foremost, the RFCs describing the architectural aspects of IPv6 addressing explicitly state, refer and repeat this apparently immutable value: Addressing Architecture [RFC4291], Reserved Interface Identifiers [RFC5453], ILNP [RFC6741]. Customer Edge routers impose /64 for their interfaces [RFC7084]. Only the IPv6 Subnet Model [RFC5942] refers to the assumption of /64 prefix length as a potential implementation error.

Numerous IPv6-over-foo documents make mandatory statements with respect to the 64-bit length of the Interface ID to be used during the Stateless Autoconfiguration. These documents include [RFC2464] (Ethernet), [RFC2467] (FDDI), [RFC2470] (Token Ring), [RFC2492] (ATM), [RFC2497] (ARCnet), [RFC2590] (Frame Relay), [RFC3146] (IEEE 1394), [RFC4338] (Fibre Channel), [RFC4944] (IEEE 802.15.4), [RFC5072] (PPP), [RFC5121] [RFC5692] (IEEE 802.16), [RFC2529] (6over4), [RFC5214] (ISATAP), [I-D.templin-aerolink] (AERO), [I-D.ietf-6lowpan-btle], [I-D.ietf-6man-6lobac], [I-D.brandt-6man-lowpanz].

To a lesser extent, the address configuration RFCs themselves may in some way assume the 64-bit length of an Interface ID (SLAAC for the link-local addresses, DHCPv6 for the potentially assigned EUI-64-based IP addresses, Default Router Preferences [RFC4191] for its impossibility of Prefix Length 4, Optimistic Duplicate Address Detection [RFC4429] which computes 64-bit-based collision probabilities).

The MLDv2 protocol [RFC3810] mandates all queries be sent with the fe80::/64 link-local source address prefix and subsequently bases the

querier election algorithm on the link-local subnet prefix length of length /64.

The IPv6 Flow Label Specification [RFC6437] gives an example of a 20-bit hash function generation which relies on splitting an IPv6 address in two equally-sized 64bit-length parts.

The basic transition mechanisms [RFC4213] refer to IIDs of length 64 for link-local addresses, and other transition mechanisms such as Teredo [RFC4380] assume the use of IIDs of length 64. Similar assumptions are found in 6to4 [RFC3056] and 6rd [RFC5969]. Translation-based transition mechanisms such as NAT64 and NPTv6 have some dependency on prefix length, discussed below.

The proposed method [I-D.ietf-v6ops-64share] of extending an assigned /64 prefix from a smartphone's cellular interface to its WiFi link relies on prefix length, and implicitely on the length of the Interface ID, to be valued at 64.

The CGA and HBA specifications rely on the 64-bit identifier length (see below), as do the Privacy extensions [RFC4941] and some examples in IKEv2bis [RFC5996].

464XLAT [RFC6877] explicitly mentions acquiring /64 prefixes. However, it also discusses the possibility of using the interface address on the device as the endpoint for the traffic, thus potentially removing this dependency.

[RFC2526] reserves a number of subnet anycast addresses by reserving some anycast IIDs. An anycast IID so reserved cannot be less than 7 bits long. This means that a subnet prefix length longer than /121 is not possible, and a subnet of exactly /121 would be useless since all its identifiers are reserved. It also means that half of a /120 is reserved for anycast. This could of course be fixed in the way described for /127 in [RFC6164], i.e., avoiding the use of anycast within a /120 subnet.

While preparing this document, it was noted that many other IPv6 specifications refer to mandatory alignment on 64-bit boundaries, 64-bit data structures, 64-bit counters in MIBs, 64-bit sequence numbers and cookies in security, etc. Finally, the number "64" may be considered "magic" in some RFCs, e.g., 64k limits in DNS and Base64 encodings in MIME. None of this has any influence on the length of the IID, but might confuse a careless reader.

4. Possible areas of breakage

This section discusses several specific aspects of IPv6 where we can expect operational breakage with subnet prefixes other than /64.

- Multicast: [RFC3306] defines a method for generating IPv6 multicast group addresses based on unicast prefixes. This method assumes a longest network prefix of 64 bits. If a longer prefix is used, there is no way to generate a specific multicast group address using this method. In such cases the administrator would need to use an "artificial" prefix from within their allocation (a /64 or shorter) from which to generate the group address. This prefix would not correspond to a real subnet.

  Similarly [RFC3956], which specifies Embedded-RP, allowing IPv6 multicast rendezvous point addresses to be embedded in the multicast group address, would also fail, as the scheme assumes a maximum prefix length of 64 bits.

- CGA: The Cryptographically Generated Address format (CGA, [RFC3972]) is heavily based on a /64 interface identifier. [RFC3972] has defined a detailed algorithm how to generate 64-bit interface identifier from a public key and a 64-bit subnet prefix. Breaking the /64 boundary would certainly break the current CGA definition. However, CGA might benefit in a redefined version if more bits are used for interface identifier (which means shorter prefix length). For now, 59 bits are used for cryptographic purposes. The more bits are available, the stronger CGA could be. Conversely, longer prefixes would weaken CGA.

- NAT64: Both stateless [RFC6052] NAT64 and stateful NAT64 [RFC6146] are flexible for the prefix length. [RFC6052] has defined multiple address formats for NAT64. In Section 2 "IPv4-Embedded IPv6 Prefix and Format" of [RFC6052], the network-specific prefix could be one of /32, /40, /48, /56, /64 and /96. The remaining part of the IPv6 address is constructed by a 32-bit IPv4 address, a 8-bit u byte and a variable length suffix (there is no u byte and suffix in the case of 96-bit Well-Known Prefix). NAT64 is therefore OK with a boundary out to /96, but not longer.

- NPTv6: IPv6-to-IPv6 Network Prefix Translation [RFC6296] is also bound to /64 boundary. NPTv6 maps a /64 prefix with other /64 prefix. When the NPTv6 Translator is configured with a /48 or shorter prefix, the 64-bit interface identifier is kept unmodified during translation. However, the /64 boundary might be broken as long as the "inside" and "outside" prefix has the same length.

- o ILNP: Identifier-Locator Network Protocol (ILNP) [RFC6741] is designed around the /64 boundary, since it relies on locally unique 64-bit interface identifiers. While a re-design to use longer prefixes is not inconceivable, this would need major changes to the existing specification for the IPv6 version of ILNP.

- o shim6: The Multihoming Shim Protocol for IPv6 (shim6) [RFC5533] in its insecure form treats IPv6 address as opaque 128-bit objects. However, to secure the protocol against spoofing, it is essential to either use CGAs (see above) or Hash-Based Addresses (HBA) [RFC5535]. Like CGAs, HBAs are generated using a procedure that assumes a 64-bit identifier. Therefore, in effect, secure shim6 is affected by the /64 boundary exactly like CGAs.

- o others?

It goes without saying that if prefixes longer than /64 are to be used, all hosts must be capable of generating IIDs shorter than 64 bits, in order to follow the auto-configuration procedure correctly [RFC4862]. There is however the rather special case of the link-local prefix. While RFC 4862 is careful not to define any specific length of link-local prefix within fe80::/10, operationally there would be a problem unless all hosts on a link use IIDs of the same length to configure a link-local address during reboot. Typically today the choice of 64 bits for the link-local IID length is hard-coded per interface. There might be no way to change this except conceivably by manual configuration, which will be impossible if the host concerned has no local user interface.

5. Experimental observations

5.1. Survey of the processing of Neighbor Discovery options with prefixes other than /64

This section provides a survey of the processing of Neighbor Discovery options which include prefixes that are different than /64.

The behavior of nodes was assessed with respect to the following options:

- o PIO-A: Prefix Information Option (PIO) [RFC4861] with the A bit set.

- o PIO-L: Prefix Information Option (PIO) [RFC4861] with the L bit set.

- o PIO-AL: Prefix Information Option (PIO) [RFC4861] with both the A and L bits set.

- o RIO: Route Information Option (RIO) [RFC4191].

In the tables below, the following notation is used:

NOT-SUP:
This option is not supported (i.e., it is ignored no matter the prefix length used).

LOCAL:
The corresponding prefix is considered "on-link".

ROUTE
The corresponding route is added to the IPv6 routing table.

IGNORE:
The Option is ignored as an error.

Operating System	PIO-A	PIO-L	PIO-AL	RIO
FreeBSD 9.0	IGNORE	LOCAL	LOCAL	NOT-SUP
Linux 3.0.0-15	IGNORE	LOCAL	LOCAL	NOT-SUP
Linux-current	IGNORE	LOCAL	LOCAL	NOT-SUP
NetBSD 5.1	IGNORE	LOCAL	LOCAL	NOT-SUP
OpenBSD-current	IGNORE	LOCAL	LOCAL	NOT-SUP
Win XP SP2	IGNORE	LOCAL	LOCAL	ROUTE
Win 7 Home Premium	IGNORE	LOCAL	LOCAL	ROUTE

Table 1: Processing of ND options with prefixes longer than /64

Operating System	PIO-A	PIO-L	PIO-AL	RIO
FreeBSD 9.0	IGNORE	LOCAL	LOCAL	NOT-SUP
Linux 3.0.0-15	IGNORE	LOCAL	LOCAL	NOT-SUP
Linux-current	IGNORE	LOCAL	LOCAL	NOT-SUP
NetBSD 5.1	IGNORE	LOCAL	LOCAL	NOT-SUP
OpenBSD-current	IGNORE	LOCAL	LOCAL	NOT-SUP
Win XP SP2	IGNORE	LOCAL	LOCAL	ROUTE
Win 7 Home Premium	IGNORE	LOCAL	LOCAL	ROUTE

Table 2: Processing of ND options with prefixes shorter than /64

The results obtained can be summarized as follows:

- o the "A" bit in the Prefix Information Options is honored only if the prefix length is 64.

- o the "L bit in the Prefix Information Options is honored for any arbitrary prefix length (whether shorter or longer than /64).

- o nodes that support the Route Information Option, allow such routes to be specified with prefixes of any arbitrary length (whether shorter or longer than /64)

5.2. Other Observations

Participants in the V6OPS working group have indicated that some forwarding devices have been shown to work correctly with long prefix masks such as /80 or /96. Indeed, it is to be expected that longest prefix match based forwarding will work for any prefix length, and no reports of this failing have been noted. Also, DHCPv6 is in widespread use without any dependency on the /64 boundary. Reportedly, there are deployments of /120 subnets configured using DHCPv6.

It has been reported that at least one type of switch has a content-addressable memory limited to 144 bits. This means that filters cannot be defined based on 128-bit addresses and two 16-bit port numbers; the longest prefix that could be used in such a filter is /112.

There have been unconfirmed assertions that some routers have a performance drop-off for prefixes longer than /64, due to design issues.

More input with practical observations is welcomed.

6. Privacy issues

The length of the interface identifier has implications for privacy [I-D.ietf-6man-ipv6-address-generation-privacy]. In any case in which the value of the identifier is intended to be hard to guess, whether or not it is cryptographically generated, it is apparent that more bits are better. For example, if there are only 20 bits to be guessed, at most just over a million guesses are needed, today well within the capacity of a low cost attack mechanism. It is hard to state in general how many bits are enough to protect privacy, since this depends on the resources available to the attacker, but it seems clear that a privacy solution needs to resist an attack requiring billions rather than millions of guesses. Trillions would be better, suggesting that at least 40 bits should be available. Thus we can argue that subnet prefixes longer than say /80 might raise privacy concerns by making the IID guessable.

A prefix long enough to limit the number of addresses comparably to an IPv4 subnet, such as /120, would create exactly the same situation for privacy as IPv4. In particular, a host would be forced to pick a new IID when roaming to a new network, to avoid collisions. An argument could be made that since this reduces traceability, it is a good thing from a privacy point of view.

7. Implementation and deployment issues

From an early stage, implementations and deployments of IPv6 assumed the /64 subnet size, even though routing was based on variable-length subnet masks of any length. As shown above, this became anchored in many specifications (Section 3) and in important aspects of implementations commonly used in local area networks (Section 5). In fact, a programmer might be lulled into assuming a comfortable rule of thumb that subnet prefixes are always /64 and an IID is always of length 64. Apart from the limited evidence in Section 5.1, we cannot tell without code inspections or tests whether existing stacks are able to handle a flexible IID length, or whether they would require modification to do so.

The main practical consequence of the existing specifications is that deployments in which longer subnet prefixes are used cannot make use of SLAAC-configured addresses, and require either statically configured addresses or DHCPv6. To reverse this argument, if it was

considered desirable to allow auto-configured addresses with subnet prefixes longer than /64, all of the specifications identified above as depending on /64 would have to be modified, with due regard to interoperability with unmodified stacks. In fact [I-D.ietf-6man-stable-privacy-addresses] allows for this possibility. Then modified stacks would have to be developed and deployed. It might be the case that some stacks contain dependencies on the /64 boundary which are not directly implied by the specifications, and any such hidden dependencies would also need to be found and removed.

Typical IP Address Management (IPAM) tools treat /64 as the default subnet size, but allow users to specify longer subnet prefixes if desired. Clearly, all IPAM tools and network management systems would need to be checked in detail.

Some implementation issues concerning prefix assignment are worth mentioning.

1. It is sometimes suggested that assigning a prefix such as /48 or /56 to every user site (including the smallest) as recommended by [RFC6177] is wasteful. In fact, the currently released unicast address space, 2000::/3, contains 35 trillion /48 prefixes ((2**45 = 35,184,372,088,832). With 2000::/3 and 0::/3 currently committed, we still have 75% of the address space in reserve. Thus there is no objective risk of prefix depletion by assigning /48 or /56 prefixes. This should be considered when evaluating the scenario of Section 2.1.

2. Some have argued that more prefix bits are needed to allow a hierarchical addressing scheme within a campus or corporate network. However, flat routing is widely and successfully used within rather large networks, with hundreds of routers and thousands of end systems. Therefore there is no objective need for additional prefix bits to support hierarchy and aggregation.

3. Some network operators wish to know and audit which nodes are active on a network, especially those that are allowed to communicate off link or off site. They may also wish to limit the total number of active addresses and sessions that can be sourced from a particular host, LAN or site, in order to prevent potential resource depletion attacks or other problems spreading beyond a certain scope of control. It has been argued that this type of control would be easier if only long network prefixes with relatively small numbers of possible hosts per network were used, reducing the discovery problem.

We now list some practical effects of the fixed /64 boundary.

- Everything is the same. Compared to IPv4, there is no more calculating (leaf) subnet sizes, no more juggling between subnets, fewer errors.

- There are always enough addresses in any subnet to add one or more devices. There might be other limits, but addressing will never get in the way.

- Adding a subnet is easy - just take the next /64. No estimates, calculations, consideration or judgment is needed.

- Router configurations are easier to understand.

- Documentation is easier to write and easier to read; training is easier.

8. Conclusion

Summary of pros and cons; risks (write this bit last!)

9. Security Considerations

In addition to the privacy issues mentioned in Section 6, and the issues mentioned with CGAs and HBAs in Section 4, the length of the subnet prefix affects the matter of defence against scanning attacks [I-D.ietf-opsec-ipv6-host-scanning]. Assuming the attacker has discovered or guessed the prefix length, a longer prefix reduces the space that the attacker needs to scan, e.g., to only 256 addresses if the prefix is /120. On the other hand, if the attacker has not discovered the prefix length and assumes it to be /64, routers can trivially discard attack packets that do not fall within an actual subnet.

However, assume that an attacker finds one valid address A and then starts a scanning attack by scanning "outwards" from A, by trying A+1, A-1, A+2, A-2, etc. This attacker will easily find all hosts in any subnet with a long prefix, because they will have addresses close to A. We therefore conclude that any prefix containing densely packed valid addresses is vulnerable to a scanning attack, without the attacker needing to guess the prefix length. Therefore, to preserve IPv6's advantage over IPv4 in resisting scanning attacks, it is important that subnet prefixes are short enough to allow sparse allocation of identifiers within each subnet. The considerations are similar to those for privacy, and we can again argue that prefixes longer than say /80 might significantly increase vulnerability. Ironically, this argument is exactly converse to the argument for longer prefixes to resist an ND cache attack, as described in Section 2.2.

Denial of service attacks related to Neighbor Discovery are discussed in [RFC6583]. One of the mitigations suggested by that document is "sizing subnets to reflect the number of addresses actually in use", but the fact that this greatly simplifies scanning attacks is not noted. For further discussion of scanning attacks, see [I-D.ietf-opsec-ipv6-host-scanning].

Note that, although not known at the time of writing, there might be other resource exhaustion attacks available, similar in nature to the ND cache attack. We cannot exclude that such attacks might be exacerbated by sparsely populated subnets such as a /64. It should also be noted that this analysis assumes a conventional deployment model with a significant number of end-systems located in a single LAN broadcast domain. Other deployment models might lead to different conclusions.

10. IANA Considerations

This document requests no action by IANA.

11. Acknowledgements

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12. Change log [RFC Editor: Please remove]

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13. References

13.1. Normative References

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