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IPv6 Unicast Address Assignment Considerations

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Abstract

One fundamental aspect of any IP communications infrastructure is its addressing plan. With its new address architecture and allocation policies, the introduction of IPv6 into a network means that network designers and operators need to reconsider their existing approaches to network addressing. Lack of guidelines on handling this aspect of network design could slow down the deployment and integration of IPv6. This document aims to provide the information and recommendations relevant to planning the addressing aspects of IPv6 deployments. The document also provides IPv6 addressing case studies for both an enterprise and an ISP network.

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1. Introduction

The Internet Protocol Version 6 (IPv6) Addressing Architecture [RFC4291] defines three main types of addresses: unicast, anycast, and multicast. This document focuses on unicast addresses, for which there are currently two principal allocated types: Globally Unique Addresses ('globals') [RFC3587] and Unique Local IPv6 Addresses (ULAs) [RFC4193]. In addition, until recently there has been the 'experimental' 6bone address space [RFC3701], though its use has been deprecated since June 2006 [RFC3701].

The document covers aspects that should be considered during IPv6 deployment for the design and planning of an addressing scheme for an IPv6 network. The network's IPv6 addressing plan may be for an IPv6-only network, or for a dual-stack infrastructure where some or all devices have addresses in both protocols. These considerations will help an IPv6 network designer to efficiently and prudently assign the IPv6 address space that has been allocated to their organization.

The address assignment considerations are analyzed separately for the two major components of the IPv6 unicast addresses -- namely, 'Network-Level Addressing' (the allocation of subnets) and the 'interface-id' (the identification of the interface within a subnet). Thus, the document includes a discussion of aspects of address assignment to nodes and interfaces in an IPv6 network. Finally, the document provides two examples of deployed addressing plans in a service provider (ISP) and an enterprise network.

Parts of this document highlight the differences that an experienced IPv4 network designer should consider when planning an IPv6 deployment, for example:

- IPv6 devices will more likely be multi-addressed in comparison with their IPv4 counterparts.
- The practically unlimited size of an IPv6 subnet (2^64 bits) reduces the requirement to size subnets to device counts for the purposes of (IPv4) address conservation.
- The vastly increased subnet size has implications on the threat of address-based host scanning and other scanning techniques, as discussed in [RFC5157].

We do not discuss here how a site or ISP should proceed with acquiring its globally routable IPv6 address prefix. In each case, the prefix received is either provider assigned (PA) or provider independent (PI).

We do not discuss PI policy here. The observations and recommendations of this text are largely independent of the PA or PI nature of the address block being used. At this time, we assume that when an IPv6 network changes provider, typically it will need to undergo a renumbering process, as described in [RFC4192]. A separate document [THINKABOUT] makes recommendations to ease the IPv6 renumbering process.

This document does not discuss implementation aspects related to the transition from the now obsoleted site-local addresses to ULAs. Some implementations know about site-local addresses even though they are deprecated, and do not know about ULAs even though they represent current specification. As a result, transitioning between these types of addresses may cause difficulties.

2. Network-Level Addressing Design Considerations

This section discusses the kind of IPv6 addresses used at the network level for the IPv6 infrastructure. The kind of addresses that can be considered are Globally Unique Addresses and ULAs. We also comment here on the deprecated 6bone address space.

2.1. Globally Unique Addresses

The most commonly used unicast addresses will be Globally Unique Addresses ('globals'). No significant considerations are necessary if the organization has an address space assignment and a single prefix is deployed through a single upstream provider.

However, a multihomed site may deploy addresses from two or more service-provider-assigned IPv6 address ranges. Here, the network administrator must have awareness on where and how these ranges are used on the multihomed infrastructure environment. The nature of the usage of multiple prefixes may depend on the reason for multihoming (e.g., resilience failover, load balancing, policy-based routing, or multihoming during an IPv6 renumbering event). IPv6 introduces improved support for multi-addressed hosts through the IPv6 default address selection methods described in RFC 3484 [RFC3484]. A multihomed host may thus have two or more addresses, one per prefix (provider), and select source and destination addresses to use as described in that RFC. However, multihoming also has some operational and administrative burdens besides choosing multiple addresses per interface [RFC4218] [RFC4219].

2.2. Unique Local IPv6 Addresses

ULAs have replaced the originally conceived site-local addresses in the IPv6 addressing architecture, for reasons described in [RFC3879]. ULAs improve on site-locals by offering a high probability of the global uniqueness of the prefix used, which can be beneficial when there is (deliberate or accidental) leakage or when networks are merged. ULAs are akin to the private address space [RFC1918] assigned for IPv4 networks, except that in IPv6 networks we may expect to see ULAs used alongside global addresses, with ULAs used internally and globals used externally. Thus, use of ULAs does not imply use of NAT for IPv6.

The ULA address range allows network administrators to deploy IPv6 addresses on their network without asking for a globally unique registered IPv6 address range. A ULA prefix is 48 bits, i.e., a /48, the same as the currently recommended allocation for a site from the globally routable IPv6 address space [RFC3177].

A site that wishes to use ULAs can have (a) multiple /48 prefixes (e.g., a /44) (b) one /48, or (c) a less-than-/48 prefix (e.g., a /56 or /64). In all of the above cases, the ULAs can be randomly chosen according to the principles specified in [RFC4193]. However, in case (a) the use of randomly chosen ULAs will provide suboptimal aggregation capabilities.

ULAs provide the means to deploy a fixed addressing scheme that is not affected by a change in service provider and the corresponding PA global addresses. Internal operation of the network is thus unaffected during renumbering events. Nevertheless, this type of address must be used with caution.

A site using ULAs may or may not also deploy global addresses. In an isolated network, ULAs may be deployed on their own. In a connected network that also deploys global addresses, both may be deployed, such that hosts become multi-addressed (one global and one ULA), and the IPv6 default address selection algorithm will pick the appropriate source and destination addresses to use, e.g., ULAs will be selected where both the source and destination hosts have ULAs. Because a ULA and a global site prefix are both /48 length, an administrator can choose to use the same subnetting (and host addressing) plan for both prefixes.

As an example of the problems ULAs may cause, when using IPv6 multicast within the network, the IPv6 default address selection algorithm prefers the ULA as the source address for the IPv6 multicast streams. This is NOT a valid option when sending an IPv6 multicast stream to the IPv6 Internet for two reasons. For one,

these addresses are not globally routable, so Reverse Path Forwarding checks for such traffic will fail outside the internal network. The other reason is that the traffic will likely not cross the network boundary due to multicast domain control and perimeter security policies.

In principle, ULAs allow easier network mergers than RFC 1918 addresses do for IPv4 because ULA prefixes have a high probability of uniqueness, if the prefix is chosen as described in the RFC.

2.3. 6bone Address Space

The 6bone address space was used before the Regional Internet Registries (RIRs) started to distribute 'production' IPv6 prefixes. The 6bone prefixes have a common first 16 bits in the IPv6 Prefix of 3FFE::/16. This address range has been deprecated as of 6 June 2006 [RFC3701] and must not be used on any new IPv6 network deployments. Sites using 6bone address space should renumber to production address space using procedures as defined in [RFC4192].

2.4. Network-Level Design Considerations

IPv6 provides network administrators with a significantly larger address space, enabling them to be very creative in how they can define logical and practical addressing plans. The subnetting of assigned prefixes can be done based on various logical schemes that involve factors such as:

- Using existing systems
  - translate the existing subnet numbers into IPv6 subnet IDs
  - translate the VLAN IDs into IPv6 subnet IDs
- Redesign
  - allocate according to your need
- Aggregation
  - Geographical Boundaries - by assigning a common prefix to all subnets within a geographical area.
  - Organizational Boundaries - by assigning a common prefix to an entire organization or group within a corporate infrastructure.

  * Service Type - by reserving certain prefixes for predefined services such as: VoIP, content distribution, wireless services, Internet access, security areas, etc. This type of addressing may create dependencies on IP addresses that can make renumbering harder if the nodes or interfaces supporting those services on the network are sparse within the topology.

Such logical addressing plans have the potential to simplify network operations and service offerings, and to simplify network management and troubleshooting. A very large network would not need to consider using private address space for its infrastructure devices, thereby simplifying network management.

The network designer must however keep in mind several factors when developing these new addressing schemes for networks with and without global connectivity:

- Prefix aggregation - The larger IPv6 addresses can lead to larger routing tables unless network designers are actively pursuing aggregation. While prefix aggregation will be enforced by the service provider, it is beneficial for the individual organizations to observe the same principles in their network design process.

- Network growth - The allocation mechanism for flexible growth of a network prefix, documented in RFC 3531 [RFC3531] can be used to allow the network infrastructure to grow and be numbered in a way that is likely to preserve aggregation (the plan leaves 'holes' for growth).

- ULA usage in large networks - Networks that have a large number of 'sites' that each deploy a ULA prefix that will by default be a 'random' /48 under fc00::/7 will have no aggregation of those prefixes. Thus, the end result may be cumbersome because the network will have large amounts of non-aggregated ULA prefixes. However, there is no rule to disallow large networks from using a single ULA prefix for all 'sites', as a ULA still provides 16 bits for subnetting to be used internally.

- Compact numbering of small sites - It is possible that as registry policies evolve, a small site may experience an increase in prefix length when renumbering, e.g., from /48 to /56. For this reason, the best practice is to number subnets compactly rather than sparsely, and to use low-order bits as much as possible when numbering subnets. In other words, even if a /48 is allocated, act as though only a /56 is available. Clearly, this advice does not apply to large sites and enterprises that have an intrinsic need for a /48 prefix.

- Consider assigning more than one /64 to a site - A small site may want to enable routing amongst interfaces connected to a gateway device. For example, a residential gateway that receives a /48 and is situated in a home with multiple LANs of different media types (sensor network, wired, Wi-Fi, etc.), or has a need for traffic segmentation (home, work, kids, etc.), could benefit greatly from multiple subnets and routing in IPv6. Ideally, residential networks would be given an address range of a /48 or /56 [RIPE_Nov07] such that multiple /64 subnets could be used within the residence.

2.4.1. Sizing the Network Allocation

We do not discuss here how a network designer sizes their application for address space. By default, a site will receive a /48 prefix [RFC3177]; however, different RIR service regions policies may suggest alternative default assignments or let the ISPs decide on what they believe is more appropriate for their specific case (see Section 6.5.4, "Assignments from LIRs/ISPs", of [ARIN]). The default provider allocation via the RIRs is currently a /32 [RIPE_Nov07]. These allocations are indicators for a first allocation for a network. Different sizes may be obtained based on the anticipated address usage [RIPE_Nov07]. At the time of writing, there are examples of allocations as large as /19 having been made from RIRs to providers.

2.4.2. Address Space Conservation

Despite the large IPv6 address space, which enables easier subnetting, it still is important to ensure an efficient use of this resource. Some addressing schemes, while facilitating aggregation and management, could lead to significant numbers of addresses being unused. Address conservation requirements are less stringent in IPv6, but they should still be observed.

The proposed Host-Density (HD) value [RFC3194] for IPv6 is 0.94 compared to the current value of 0.96 for IPv4. Note that with IPv6, HD is calculated for sites (e.g., on a basis of /56), instead of for addresses as with IPv4.

3. Subnet Prefix Considerations

An important part of an IPv4 addressing plan is deciding the length of each subnet prefix. Unlike in IPv4, the IPv6 addressing architecture [RFC4291] specifies that all subnets using Globally Unique Addresses and ULAs always have the same prefix length of 64 bits. (This also applies to the deprecated 6bone and site-local addresses.)

The only exception to this rule are special addresses starting with the binary value 000, such as IPv4-compatible IPv6 addresses. These exceptions are largely beyond the scope of this document.

Using a subnet prefix length other than a /64 will break many features of IPv6, including Neighbor Discovery (ND), Secure Neighbor Discovery (SEND) [RFC3971], privacy extensions [RFC4941], parts of Mobile IPv6 [RFC4866], Protocol Independent Multicast - Sparse Mode (PIM-SM) with Embedded-RP [RFC3956], and Site Multihoming by IPv6 Intermediation (SHIM6) [SHIM6], among others. A number of other features currently in development, or being proposed, also rely on /64 subnet prefixes.

Nevertheless, many IPv6 implementations do not prevent the administrator from configuring a subnet prefix length shorter or longer than 64 bits. Using subnet prefixes shorter than /64 would rarely be useful; see Appendix B.1 for discussion.

However, some network administrators have used prefixes longer than /64 for links connecting routers, usually just two routers on a point-to-point link. On links where all the addresses are assigned by manual configuration, and all nodes on the link are routers (not end hosts) that are known by the network, administrators do not need any of the IPv6 features that rely on /64 subnet prefixes, this can work. Using subnet prefixes longer than /64 is not recommended for general use, and using them for links containing end hosts would be an especially bad idea, as it is difficult to predict what IPv6 features the hosts will use in the future.

Appendix B.2 describes some practical considerations that need to be taken into account when using prefixes longer than /64 in limited cases. In particular, a number of IPv6 features use interface identifiers that have a special form (such as a certain fixed value in some bit positions). When using prefixes longer than /64, it is prudent to avoid certain subnet prefix values so that nodes who assume that the prefix is /64 will not incorrectly identify the addresses in that subnet as having a special form. Appendix B.2 describes the subnet prefix values that are currently believed to be potentially problematic; however, the list is not exhaustive and can be expected to grow in the future.

Using /64 subnets is strongly recommended, also for links connecting only routers. A deployment compliant with the current IPv6 specifications cannot use other prefix lengths. However, the V6OPS WG believes that despite the drawbacks (and a potentially expensive network redesign, if IPv6 features relying on /64 subnets are needed in the future), some networks administrators will use prefixes longer than /64.

3.1. Considerations for /64 Prefixes

Based on RFC 3177 [RFC3177], 64 bits is the prescribed subnet prefix length to allocate to interfaces and nodes.

When using a /64 subnet length, the address assignment for these addresses can be made either by manual configuration, by a Dynamic Host Configuration Protocol [RFC3315], by stateless autoconfiguration [RFC4862], or by a combination thereof [RFC3736].

Note that RFC 3177 strongly prescribes 64-bit subnets for general usage, and that stateless autoconfiguration on most link layers (including Ethernet) is only defined for 64-bit subnets. While in theory it might be possible that some future autoconfiguration mechanisms would allow longer than 64-bit prefix lengths to be used, the use of such prefixes is not recommended at this time.

4. Allocation of the IID of an IPv6 Address

In order to have a complete IPv6 address, an interface must be associated with a prefix and an Interface Identifier (IID). Section 3 of this document analyzed the prefix selection considerations. This section discusses the elements that should be considered when assigning the IID portion of the IPv6 address.

There are various ways to allocate an IPv6 address to a device or interface. The option with the least amount of caveats for the network administrator is that of EUI-64 [RFC4862] based addresses. For the manual or dynamic options, the overlap with well-known IPv6 addresses should be avoided.

4.1. Automatic EUI-64 Format Option

When using this method, the network administrator has to allocate a valid 64-bit subnet prefix. Once that allocation has been made, the EUI-64 [RFC4862] allocation procedure can assign the remaining 64 IID bits in a stateless manner. All the considerations for selecting a valid IID have been incorporated into the EUI-64 methodology.

4.2. Using Privacy Extensions

The main purpose of IIDs generated based on RFC 4941 [RFC4941] is to provide privacy to the entity using an IPv6 address. While there are no particular constraints in the usage of IPv6 addresses with IIDs as defined in [RFC4941], there are some implications to be aware of when using privacy addresses as documented in Section 4 of RFC 4941 [RFC4941]

4.3. Manual/Dynamic Assignment Option

This section discusses those IID allocations that are not implemented through stateless address configuration (Section 4.1). They are applicable regardless of the prefix length used on the link. It is out of scope for this section to discuss the various assignment methods (e.g., manual configuration, DHCPv6, etc).

In this situation, the actual allocation is done by human intervention, and consideration needs to be given to the complete IPv6 address so that it does not result in overlaps with any of the well-known IPv6 addresses:

- Subnet Router Anycast Address (Appendix B.2.5.1)
- Reserved Subnet Anycast Address (Appendix B.2.5.2)
- Addresses used by Embedded-RP (Appendix B.2.6)
- Intra-Site Automatic Tunnel Addressing Protocol (ISATAP) Addresses (Appendix B.2.7)

When using an address assigned by human intervention, it is recommended to choose IPv6 addresses that are not obvious to guess and/or to avoid any IPv6 addresses that embed IPv4 addresses used in the current infrastructure. Following these two recommendations will make it more difficult for malicious third parties to guess targets for attack, and thus reduce security threats to a certain extent.

5. Security Considerations

This document doesn’t add any new security considerations that aren’t already outlined in the security considerations of the references.

It must be noted that using subnet prefixes other than /64 breaks security mechanisms such as Cryptographically Generated Addresses (CGAs) and Hash-Based Addresses (HBAs), and thus makes it impossible to use protocols that depend on them.

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Appendix A. Case Studies

This appendix contains two case studies for IPv6 addressing schemas that have been based on the statements and considerations of this document. These case studies illustrate how this document has been used in two specific network scenarios. The case studies may serve as basic considerations for an administrator who designs the IPv6 addressing schema for an enterprise or ISP network, but are not intended to serve as a general design proposal for every kind of IPv6 network. All subnet sizes used in this appendix are for practical visualization and do not dictate RIR policy.

A.1. Enterprise Considerations

In this section, one considers a case study of a campus network that is deploying IPv6 in parallel with existing IPv4 protocols in a dual-stack environment. The specific example is the University of Southampton (UK), focusing on a large department within that network. The deployment currently spans around 1,000 hosts and over 1,500 users.

A.1.1. Obtaining General IPv6 Network Prefixes

In the case of a campus network, the site will typically take its connectivity from its National Research and Education Network (NREN). Southampton connects to JANET, the UK academic network, via its local regional network LeNSE (Learning Network South East). JANET currently has a /32 allocation from RIPE NCC. The current recommended practice is for sites to receive a /48 allocation; on this basis, Southampton has received such a prefix for its own use. The regional network also uses its own allocation from the NREN provider.

No ULA addressing is used on site. The campus is not multihomed (JANET is the sole provider), nor does it expect to change service provider, and thus does not plan to use ULAs for the (perceived) benefit of easing network renumbering. Indeed, the campus has renumbered following the aforementioned renumbering procedure [RFC4192] on two occasions, and this has proven adequate (with provisos documented in [THINKABOUT]). The campus does not see any need to deploy ULAs for in-band or out-of-band network management; there are enough IPv6 prefixes available in the site allocation for the infrastructure. In some cases, use of private IP address space in IPv4 creates problems, so University of Southampton believes that the availability of ample global IPv6 address space for infrastructure may be a benefit for many sites.

No 6bone addressing is used on site any more. Since the 6bone phaseout of June 2006 [RFC3701], most transit ISPs have begun filtering attempted use of such prefixes.

Southampton does participate in global and organizational scope IPv6 multicast networks. Multicast address allocations are not discussed here as they are not in scope for the document. It is noted that IPv6 has advantages for multicast group address allocation. In IPv4, a site needs to use techniques like GLOP [RFC3180] to pick a globally unique multicast group to use. This is problematic if the site does not use the Border Gateway Protocol (BGP) [RFC4271] and does not have an Autonomous System Number (ASN). In IPv6,0 unicast-prefix-based IPv6 multicast addresses empower a site to pick a globally unique group address based on its own unicast site or link prefix. Embedded-RP is also in use, is seen as a potential advantage for IPv6 and multicast, and has been tested successfully across providers between sites (including paths to/from the US and UK).

A.1.2. Forming an Address (Subnet) Allocation Plan

The campus has a /16 prefix for IPv4 use; in principle, 256 subnets of 256 addresses. In reality, the subnetting is muddier, because of concerns of IPv4 address conservation; subnets are sized to the hosts within them, e.g., a /26 IPv4 prefix is used if a subnet has 35 hosts in it. While this is efficient, it increases management burden when physical deployments change, and IPv4 subnets require resizing (up or down), even when DHCP is in use.

The /48 IPv6 prefix is considerably larger than the IPv4 allocation already in place at the site. It is loosely equivalent to a 'Class A' IPv4 prefix in that it has 2^16 (over 65,000) subnets, but has an effectively unlimited subnet address size (2^64) compared to 256 in the IPv4 equivalent. The increased subnet size means that /64 IPv6 prefixes can be used on all subnets, without any requirement to resize them at a later date. The increased subnet volume allows subnets to be allocated more generously to schools and departments in the campus. While address conservation is still important, it is no longer an impediment to network management. Rather, address (subnet) allocation is more about embracing the available address space and planning for future expansion.

In a dual-stack network, it was chosen to deploy the IP subnets congruently for IPv4 and IPv6. This is because the systems are still in the same administrative domains and the same geography. It is not expected to have IPv6-only subnets in production use for a while yet, outside the test beds and some early Mobile IPv6 trials. With congruent addressing, the firewall policies are also aligned for IPv4 and IPv6 traffic at the site border.

The subnet allocation plan required a division of the address space per school or department. Here, a /56 was allocated to the school level of the university; there are around 30 schools currently. A /56 of IPv6 address space equates to 256 /64 subnet allocations. Further /56 allocations were made for central IT infrastructure, the network infrastructure, and the server side systems.

A.1.3. Other Considerations

The network uses a Demilitarized Zone (DMZ) topology for some level of protection of 'public' systems. Again, this topology is congruent with the IPv4 network.

There are no specific transition methods deployed internally to the campus; everything is using the conventional dual-stack approach. There is no use of ISATAP [RFC5214] for example.

For the Mobile IPv6 early trials, there is one allocated prefix for Home Agent (HA) use. However, there has been no detailed consideration yet regarding how Mobile IPv6 usage may grow, and whether more subnets (or even every subnet) will require HA support.

The university operates a tunnel broker [RFC3053] service on behalf of the United Kingdom Education and Research Network Association (UKERNA) for JANET sites. This uses separate address space from JANET, not the university site allocation.

A.1.4. Node Configuration Considerations

Currently, stateless autoconfiguration is used on most subnets for IPv6 hosts. There is no DHCPv6 service deployed yet, beyond tests of early code releases. It is planned to deploy DHCPv6 for address assignment when robust client and server code is available (at the time of writing, the potential for this looks good, e.g., via the Internet Systems Consortium (ISC) implementation). University of Southampton is also investigating a common integrated DHCP/DNS management platform, even if the servers themselves are not co-located, including integrated DHCPv4 and DHCPv6 server configuration, as discussed in [RFC4477]. Currently, clients with statelessly autoconfigured addresses are added to the DNS manually, though dynamic DNS is an option. The network administrators would prefer the use of DHCP because they believe it gives them more management control.

Regarding the implications of the larger IPv6 subnet address space on scanning attacks [RFC5157], it is noted that all the hosts are dual-stack, and thus are potentially exposed over both protocols anyway. All addresses are published in DNS, and the site does not operate a two-faced DNS.

Currently, there is internal usage of RFC 4941 privacy addresses [RFC4941] (certain platforms ship with it on by default), but network administrators may desire to disable this (perhaps via DHCP) to ease management complexity. However, it is desired to determine the feasibility of this on all systems, e.g., for guests on wireless LAN or other user-maintained systems. Network management and monitoring should be simpler without RFC 4941 in operation, in terms of identifying which physical hosts are using which addresses. Note that RFC 4941 is only an issue for outbound connections, and that there is potential to assign privacy addresses via DHCPv6.

Manually configured server addresses are used to avoid address changes based upon change of network adaptor. With IPv6 you can pick ::53 for a DNS server, or you can pick ’random’ addresses for obfuscation, though that’s not an issue for publicly advertised addresses (dns, mx, web, etc.).

A.2. Service Provider Considerations

In this section an IPv6 addressing schema is sketched that could serve as an example for an Internet Service Provider.

Appendix A.2.1 starts with some thoughts regarding objective requirements of such an addressing schema and derives a few general rules of thumb that have to be kept in mind when designing an ISP IPv6 addressing plan.

Appendix A.2.2 illustrates the findings of Appendix A.2.1 with an exemplary IPv6 addressing schema for an MPLS-based ISP offering Internet services as well as network access services to several millions of customers.

A.2.1. Investigation of Objective Requirements for an IPv6 Addressing Schema of a Service Provider

The first step of the IPv6 addressing plan design for a service provider should identify all technical, operational, political, and business requirements that have to be satisfied by the services supported by this addressing schema.

According to the different technical constraints and business models as well as the different weights of these requirements (from the point of view of the corresponding service provider), it is very likely that different addressing schemas will be developed and deployed by different ISPs. Nevertheless, the addressing schema of Appendix A.2.2 is one possible example.

For this document, it is assumed that our exemplary ISP has to fulfill several roles for its customers such as:

- Local Internet Registry
- Network Access Provider
- Internet Service Provider

A.2.1.1. Recommendations for an IPv6 Addressing Schema from the LIR Perspective of the Service Provider

In its role as Local Internet Registry (LIR), the service provider has to care about the policy constraints of the RIRs and the standards of the IETF regarding IPv6 addressing. In this context, the following basic recommendations have to be considered and should be satisfied by the IPv6 address allocation plan of a service provider:

- As recommended in RFC 3177 [RFC3177] and in several RIR policies, "Common" customers sites (normally private customers) should receive a /48 prefix from the aggregate of the service provider. (Note: The addressing plan must be flexible enough and take into account the possible change of the minimum allocation size for end users currently under definition by the RIRs.)
- "Big customers" (like big enterprises, governmental agencies, etc.) may receive shorter prefixes according to their needs, when their needs can be documented and justified to the RIR.
- The IPv6 address allocation schema has to be able to meet the HD-ratio that is proposed for IPv6. This requirement corresponds to the demand for an efficient usage of the IPv6 address aggregate by the service provider. (Note: The currently valid IPv6 HD-ratio of 0.94 means an effective usage rate of about 22% of a /20 prefix of the service provider, on the basis of /56 assignments.)
- All assignments to customers have to be documented and stored into a database that can also be queried by the RIR.

- The LIR has to make available the means for supporting the reverse DNS mapping of the customer prefixes.

- IPv6 Address Allocation and Assignment Policies can be found at RIRs and are similar in many aspects. See [RIPE_Nov07], [RIPE_Jul07], [APNIC_IPv6], [LACNIC_IPv6], [AFRINIC_IPv6], and Section 6 of [ARIN].

A.2.1.2. IPv6 Addressing Schema Recommendations from the ISP Perspective of the Service Provider

From the ISP perspective, the following basic requirements can be identified:

- The IPv6 address allocation schema must be able to realize a maximal aggregation of all IPv6 address delegations to customers into the address aggregate of the service provider. Only this provider aggregate will be routed and injected into the global routing table (DFZ, "Default-Free Zone"). This strong aggregation keeps the routing tables of the DFZ small and eases filtering and access control very much.

- The IPv6 addressing schema of the SP should contain optimal flexibility since the infrastructure of the SP will change over time with new customers, transport technologies, and business cases. The requirement of optimal flexibility is contrary to the recommendation of strong IPv6 address aggregation and efficient address usage, but each SP has to decide which of these requirements to prioritize.

- While keeping the multilevel network hierarchy of an ISP in mind, note that due to addressing efficiency reasons, not all hierarchy levels can and should be mapped into the IPv6 addressing schema of an ISP. Sometimes it is much better to implement a more "flat" addressing for the ISP network than to lose big chunks of the IPv6 address aggregate in addressing each level of network hierarchy. (Note: In special cases, it is even recommended for really "small" ISPs to design and implement a totally flat IPv6 addressing schema without any level of hierarchy.)

- A decoupling of provider network addressing and customer addressing is recommended. (Note: A strong aggregation (e.g., on POP, Aggregation Router (AG), or Label Edge Router (LER) level) limits the numbers of customer routes that are visible within the ISP network, but also brings down the efficiency of the IPv6 addressing schema. That’s why each ISP has to decide how many internal aggregation levels it wants to deploy.)

A.2.1.3. IPv6 Addressing Schema Recommendations from the Network Access Provider Perspective of the Service Provider

As already done for the LIR and the ISP roles of the SP it is also necessary to identify requirements that come from its Network Access Provider role. Some of the basic requirements are:

- The IPv6 addressing schema of the SP, it must be chosen in a way that it can handle new requirements that are triggered from customer side. For instance, this can be the customer's growing needs for IPv6 addresses as well as customer-driven modifications within the access network topology (e.g., when the customer moves from one point of network attachment (POP) to another). (See Appendix A.2.3.4, "Changing the Point of Network Attachment".)

- For each IPv6 address assignment to customers, a "buffer zone" should be reserved that allows the customer to grow in its addressing range without renumbering or assignment of additional prefixes.

- The IPv6 addressing schema of the SP must deal with multiple attachments of a single customer to the SP network infrastructure (i.e., multihomed network access with the same SP).

These few requirements are only part of the requirements a service provider has to investigate and keep in mind during the definition phase of its addressing architecture. Each SP will most likely add more constraints to this list.

A.2.1.4. A Few Rules of Thumb for Designing an ISP IPv6 Addressing Architecture

As a result of the above enumeration of requirements regarding an ISP IPv6 addressing plan, the following design "rules of thumb" have been derived:

- No "One size fits all". Each ISP must develop its own IPv6 address allocation schema depending on its concrete business needs. It is not practical to design one addressing plan that fits for all kinds of ISPs (small / big, routed / MPLS-based, access / transit, LIR / No LIR, etc.).

- The levels of IPv6 address aggregation within the ISP addressing schema should strongly correspond to the implemented network structure, and their number should be minimized because of efficiency reasons. It is assumed that the SP's own

infrastructure will be addressed in a fairly flat way, whereas part of the customer addressing architecture should contain several levels of aggregation.

- Keep the number of IPv6 customer routes inside your network as small as possible. A totally flat customer IPv6 addressing architecture without any intermediate aggregation level will lead to lots of customer routes inside the SP network. A fair trade-off between address aggregation levels (and hence the size of the internal routing table of the SP) and address conservation of the addressing architecture has to be found.

- The ISP IPv6 addressing schema should provide maximal flexibility. This has to be realized for supporting different sizes of customer IPv6 address aggregates ("big" customers vs. "small" customers) as well as to allow future growth rates (e.g., of customer aggregates) and possible topological or infrastructural changes.

- A limited number of aggregation levels and sizes of customer aggregates will ease the management of the addressing schema. This has to be weighed against the previous "rule of thumb" -- flexibility.

A.2.2. Exemplary IPv6 Address Allocation Plan for a Service Provider

In this example, the service provider is assumed to operate an MPLS-based backbone and to implement IPv6 Provider Edge Routers (6PE) [RFC4798] to provide IPv6 backbone transport between the different locations (POPs) of a fully dual-stacked network access and aggregation area.

In addition, it is assumed that the service provider:

- has received a /20 from its RIR

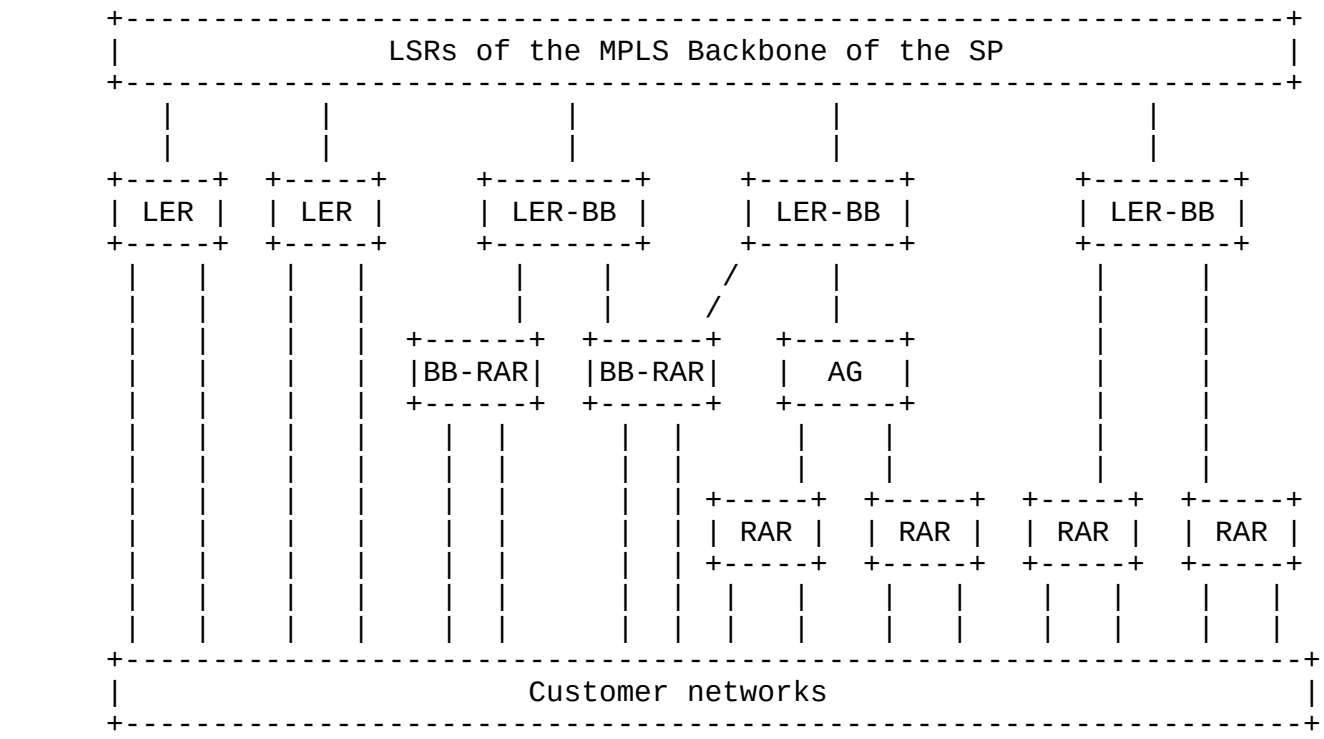
- operates its own LIR

- has to address its own IPv6 infrastructure

- delegates prefixes from this aggregate to its customers

This addressing schema should illustrate how the /20 IPv6 prefix of the SP can be used to address the SP’s own infrastructure and to delegate IPv6 prefixes to its customers, following the above-mentioned requirements and rules of thumb as far as possible.

The figure below summarizes the device types in an SP network and the typical network design of a MPLS-based service provider. The network hierarchy of the SP has to be taken into account for the design of an IPv6 addressing schema; it defines the basic shape of the addressing schema and the various levels of aggregation.



LSR Label Switch Router
LER Label Edge Router
LER-BB Broadband Label Edge Router
RAR Remote Access Router
BB-RAR Broadband Remote Access Router
AG Aggregation Router

Exemplary Service Provider Network

The following should be taken into consideration when making the basic design decisions for the exemplary service provider IPv6 addressing plan regarding customer prefixes.

- The prefixes assigned to all customers behind the same LER (or LER-BB) are aggregated under one LER prefix. This ensures that the number of labels that have to be used for 6PE is limited and hence provides strong MPLS label conservation.

- The /20 prefix of the SP is separated into 3 different pools that are used to allocate IPv6 prefixes to the customers of the SP:

  1. A pool (e.g., /24) for satisfying the addressing needs of really "big" customers (as defined in Appendix A.2.2.1.1) that need IPv6 prefixes larger than /48 (e.g., /32). These customers are assumed to be connected to several POPs of the access network, so that this customer prefix will be visible in each of these POPs.

  2. A pool (e.g., /24) for the LERs with direct customer connections (e.g., dedicated line access) and without an additional aggregation area between the customer and the LER. (These LERs are mostly connected to a limited number of customers because of the limited number of interfaces/ports.)

  3. A larger pool (e.g., 14*/24) for LERs (or LER-BBs) that serve a high number of customers that are normally connected via some kind of aggregation network (e.g., DSL customers behind a BB-RAR or dial-in customers behind a RAR).

- The IPv6 address delegation within each pool (the end customer delegation or the aggregates that are dedicated to the LER itself) should be chosen with an additional buffer zone of 100-300% for future growth. That is, 1 or 2 additional prefix bits should be reserved according to the expected future growth rate of the corresponding customer or the corresponding network device aggregate.

A.2.2.1. Defining an IPv6 Address Allocation Plan for Customers of the Service Provider

A.2.2.1.1. "Big" Customers

The SP’s "big" customers receive their prefix from the /24 IPv6 address aggregate that has been reserved for their "big" customers. A customer is considered a "big" customer if it has a very complex network infrastructure and/or huge IPv6 address needs (e.g., because of very large customer numbers) and/or several uplinks to different POPs of the SP network.

The assigned IPv6 address prefixes can have a prefix length in the range 32-48 and for each assignment a 100 or 300% future growing zone is marked as "reserved" for this customer. For instance, this means that with a delegation of a /34 to a customer the corresponding /32 prefix (which contains this /34) is reserved for the customer’s future usage.

The prefixes for the "big" customers can be chosen from the corresponding "big customer" pool by either using an equidistant algorithm or using mechanisms similar to the Sparse Allocation Algorithm (SAA) [RIPE_Nov07].

A.2.2.1.2. "Common" Customers

All customers that are not "big" customers are considered as "common" customers. They represent the majority of customers, hence they receive a /48 out of the IPv6 customer address pool of the LER where they are directly connected or aggregated.

Again a 100-300% future growing IPv6 address range is reserved for each customer, so that a "common" customer receives a /48 allocation but has a /47 or /46 reserved.

(Note: If it is obvious that the likelihood of needing a /47 or /46 in the future is very small for a "common" customer, then no growing buffer should be reserved for it, and only a /48 will be assigned without any growing buffer.)

In the network access scenarios where the customer is directly connected to the LER, the customer prefix is directly taken out of the customer IPv6 address aggregate (e.g., /38) of the corresponding LER.

For other cases (e.g., the customer is attached to a RAR that is itself aggregated to an AG or to a LER-BB), at least 2 different approaches are possible.

1) Mapping of Aggregation Network Hierarchy into Customer IPv6 Addressing Schema. The aggregation network hierarchy could be mapped into the design of the customer prefix pools of each network level in order to achieve a maximal aggregation at the LER level as well as at the intermediate levels. (Example: Customer - /48, RAR - /38, AG - /32, LER-BB - /30). At each network level, an adequate growing zone should be reserved. (Note: Of course, this approach requires some "fine tuning" of the addressing schema based on a very good knowledge of the Service Provider network topology including actual growing ranges and rates.)

   When the IPv6 customer address pool of a LER (or another device of the aggregation network -- AG or RAR) is exhausted, the related LER (or AG or RAR) prefix is shortened by 1 or 2 bits (e.g., from /38 to /37 or /36) so that the originally reserved growing zone can be used for further IPv6 address allocations to

customers. In the case where this growing zone is exhausted as well, a new prefix range from the corresponding pool of the next-higher hierarchy level can be requested.

2) "Flat" Customer IPv6 Addressing Schema. The other option is to allocate all the customer prefixes directly out of the customer IPv6 address pool of the LER where the customers are attached and aggregated and to ignore the intermediate aggregation network infrastructure. Of course, this approach leads to a higher amount of customer routes at the LER and aggregation network level, but it takes a great amount of complexity out of the addressing schema. Nevertheless, the aggregation of the customer prefixes to one prefix at the LER level is realized as required above.

Note: The handling of changes (e.g., technically triggered changes) within the ISP access network is discussed briefly in Appendix A.2.3.5.

If the actual observed growing rates show that the reserved growing zones are not needed, then they can be freed and used for assignments for prefix pools to other devices at the same level of the network hierarchy.

A.2.2.2. Defining an IPv6 Address Allocation Plan for the Service Provider Network Infrastructure

For the IPv6 addressing of the SP's own network infrastructure, a /32 (or /40) from the "big" customers address pool can be chosen.

This SP infrastructure prefix is used to code the network infrastructure of the SP by assigning a /48 to every POP/location and using (for instance) a /56 for coding the corresponding router within this POP. Each SP internal link behind a router interface could be coded using a /64 prefix. (Note: While it is suggested to choose a /48 for addressing the POP/location of the SP network, it is left to each SP to decide what prefix length to assign to the routers and links within the POP.)

The IIDs of the router interfaces may be generated by using EUI-64 or through plain manual configuration, e.g., for coding additional network or operational information into the IID.

Again, it is assumed that 100-300% growing zones are needed for each level of network hierarchy, and additional prefix bits may be assigned to POPs and/or routers if needed.

Loopback interfaces of routers may be chosen from the first /64 of the /56 router prefix (in the example above).

(Note: The /32 (or /40) prefix that has been chosen for addressing the SP's own IPv6 network infrastructure leaves enough space to code additional functionalities like security levels or private and test infrastructure, although such approaches haven't been considered in more detail for the above-described SP until now.)

Point-to-point links to customers (e.g., PPP links, dedicated lines, etc.) may be addressed using /126 prefixes out of the first /64 of the access routers that could be reserved for this reason.

A.2.3. Additional Remarks

A.2.3.1. ULA

There are no compelling reasons for service providers to use ULAs. See Section 2.2.

ULAs could be used inside the SP network in order to have an additional "site-local scoped" IPv6 address for the SP's own infrastructure, for instance, for network management reasons and in order to have an addressing schema that can't be reached from outside the SP network.

When ULAs are used, it is possible to map the proposed internal IPv6 addressing of the SP's own network infrastructure (as described in Appendix A.2.2.2) directly to the ULA addressing schema by substituting the /48 POP prefix with a /48 ULA site prefix.

A.2.3.2. Multicast

IPv6 multicast-related addressing issues are out of the scope of this document.

A.2.3.3. POP Multihoming

POP multihoming (or better, LER multihoming) of customers with the same SP can be realized within the proposed IPv6 addressing schema of the SP by assigning multiple LER-dependent prefixes to this customer (i.e., considering each customer location as a single customer) or by choosing a customer prefix out of the pool of "big" customers. The second solution has the disadvantage that in every LER where the customer is attached, this prefix will appear inside the IGP routing table, thus requiring an explicit MPLS label.

Note: The negative effects (described above) of POP/LER multihoming on the addressing architecture in the SP access network are not resolved by implementing the Site Multihoming by IPv6 Intermediation (SHIM6) approach. SHIM6 only targets a mechanism for dealing with multiple prefixes in end systems. The SP is expected to have unaggregated customer prefixes in its internal routing tables.

A.2.3.4. Changing the Point of Network Attachment

In the possible case that a customer has to change its point of network attachment to another POP/LER within the ISP access network, two different approaches can be applied, assuming that the customer uses PA addresses out of the SP aggregate:

1) The customer has to renumber its network with an adequate customer prefix out of the aggregate of the corresponding LER/RAR of its new network attachment. To minimize the administrative burden for the customer, the prefix should be of the same size as the former. This conserves the IPv6 address aggregation within the SP network (and the MPLS label space) but adds additional burden to the customer. Hence, this approach will most likely only be chosen in the case of "small customers" with temporary addressing needs and/or prefix delegation with address autoconfiguration.

2) The customer does not need to renumber its network and keeps its address aggregate.

   This approach leads to additional more-specific routing entries within the IGP routing table of the LER and will hence consume additional MPLS labels, but it is totally transparent to the customer. Because this results in additional administrative effort and will stress the router resources (label space, memory) of the ISP, this solution will only be offered to the most valuable customers of an ISP (e.g., "big customers" or "enterprise customers").

   Nevertheless, the ISP again has to find a fair trade-off between customer renumbering and sub-optimal address aggregation (i.e., the generation of additional more-specific routing entries within the IGP and the waste of MPLS label space).

A.2.3.5. Restructuring of SP (Access) Network and Renumbering

A technically triggered restructuring of the SP (access) network (for instance, because of split of equipment or installation of new equipment) should not lead to a customer network renumbering. This challenge should be handled in advance by an intelligent network design and IPv6 address planning.

In the worst case, the customer network renumbering could be avoided through the implementation of more-specific customer routes. (Note: Since this kind of network restructuring will mostly happen within the access network (at the level) below the LER, the LER aggregation level will not be harmed and the more-specific routes will not consume additional MPLS label space.)

A.2.3.6. Extensions Needed for the Later IPv6 Migration Phases

The proposed IPv6 addressing schema for an SP needs some slight enhancements / modifications for the later phases of IPv6 integration, for instance, when the whole MPLS backbone infrastructure (LDP, IGP, etc.) is realized over IPv6 transport, and an IPv6 addressing of the LSRs is needed. Other changes may be necessary as well but should not be explained at this point.

Appendix B. Considerations for Subnet Prefixes Different than /64

B.1. Considerations for Subnet Prefixes Shorter than /64

An allocation of a prefix shorter then 64 bits to a node or interface is considered bad practice. One exception to this statement is when using 6to4 technology where a /16 prefix is utilized for the pseudo-interface [RFC3056]. The shortest subnet prefix that could theoretically be assigned to an interface or node is limited by the size of the network prefix allocated to the organization.

A possible reason for choosing the subnet prefix for an interface shorter than /64 is that it would allow more nodes to be attached to that interface compared to a prescribed length of 64 bits. The prescribed /64 does include 2 functional bits, the ’g’ bit and the inverted ’u’ (universal/local) bit and these can not be chosen at will. However, a larger address space then a /64 is unnecessary for most networks, considering that 2^62 provides plenty of node addresses.

The subnet prefix assignments can be made by manual configuration, by a stateful Host Configuration Protocol [RFC3315], by a stateful prefix delegation mechanism [RFC3633], or implied by stateless autoconfiguration from prefix Router Advertisements (RAs).

B.2. Considerations for Subnet Prefixes Longer than /64

The following subsections describe subnet prefix values that should be avoided in deployments because nodes who assume that the subnet prefix is /64 could treat them incorrectly.

B.2.1. /126 Addresses

126-bit subnet prefixes are typically used for point-to-point links similar to a the IPv4 address-conservative /30 allocation for point-to-point links. The usage of this subnet address length does not lead to any considerations beyond those discussed earlier in this section, particularly those related to the 'u' and 'g' bits (see B.2.4.

B.2.2. /127 Addresses

The usage of the /127 addresses, the equivalent of IPv4's RFC 3021 [RFC3021], is not valid and should be strongly discouraged as documented in RFC 3627 [RFC3627].

B.2.3. /128 Addresses

The 128-bit address prefix may be used in those situations where we know that one, and only one, address is sufficient. Example usage would be the off-link loopback address of a network device.

When choosing a 128 bit prefix, it is recommended to take the 'u' and 'g' bits into consideration and to make sure that there is no overlap with any of the following well-known addresses:

- Subnet Router Anycast Address
- Reserved Subnet Anycast Address
- Addresses used by Embedded-RP
- ISATAP Addresses

B.2.4. EUI-64 'u' and 'g' Bits

When using subnet prefix lengths other than /64, the interface identifier cannot be in Modified EUI-64 format as required by [RFC4291]. However, nodes not aware that a prefix length other than /64 is used might still think it's an EUI-64; therefore, it's prudent to take into account the following points when setting the bits.

Address space conservation is the main motivation for using a subnet prefix length longer than 64 bits; however, this kind of address conservation is of little benefit compared with the additional considerations one must make when creating and maintaining an IPv6 addressing plan.

The address assignment can be made either by manual configuration or by a stateful Host Configuration Protocol [RFC3315].

When assigning a subnet prefix of more then 70 bits, according to RFC 4291 [RFC4291], 'u' and 'g' bits (the 71st and 72nd bit, respectively) need to be taken into consideration and should be set correctly.

The 71st bit of a IPv6 address is the inverted 'u' (universal/local) bit and is used to determine whether the address is universally or locally administered. If 1, the IEEE, through the designation of a unique company ID, has administered the address. If 0, the address is locally administered. The network administrator has overridden the manufactured address and specified a different address.

The 'g' (the individual/group) bit is the 72nd bit and is used to determine whether the address is an individual address (unicast) or a group address (multicast). If '0', the address is a unicast address. If '1', the address is a multicast address.

In current IPv6 protocol stacks, the relevance of the 'u' and 'g' bits is marginal and typically will not give an error when configured wrongly; however, future implementations may turn out differently if they process the 'u' and 'g' bits in IEEE-like behavior.

When using subnet lengths longer then 64 bits, it is important to avoid selecting addresses that may have a predefined use and could confuse IPv6 protocol stacks. The alternate usage may not be a simple unicast address in all cases. The following points should be considered when selecting a subnet length longer then 64 bits.

B.2.5. Anycast Addresses

B.2.5.1. Subnet Router Anycast Address

RFC 4291 [RFC4291] provides a definition for the required Subnet Router Anycast Address as follows:

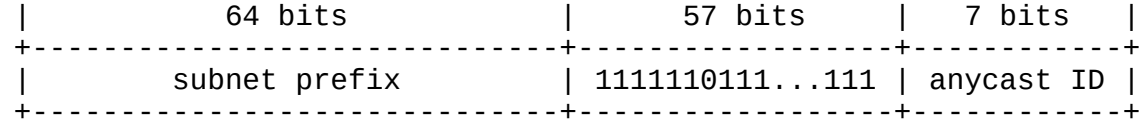
It is recommended to avoid allocating this IPv6 address to a device that expects to have a normal unicast address.

B.2.5.2. Reserved IPv6 Subnet Anycast Addresses

RFC 2526 [RFC2526] stated that within each subnet, the highest 128 interface identifier values are reserved for assignment as subnet anycast addresses.

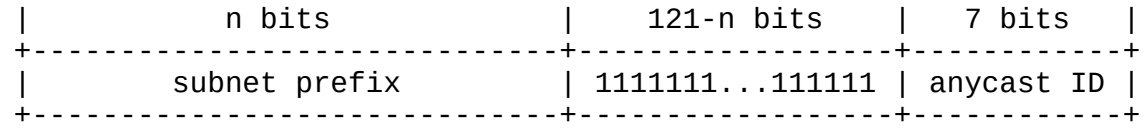
The construction of a reserved subnet anycast address depends on the type of IPv6 addresses used within the subnet, as indicated by the format prefix in the addresses.

The first type of Subnet Anycast addresses have been defined as follows for the Modified EUI-64 format:



The anycast address structure implies that it is important to avoid creating a subnet prefix where the bits 65 to 121 are defined as "1111110111...111" (57 bits in total) in order to prevent confusion.

For other IPv6 address types (that is, with format prefixes other than those listed above), the interface identifier is not in 64-bit extended unique identifier (EUI-64) format and may not be 64 bits in length. The reserved subnet anycast addresses for such address types are constructed as follows:



It is recommended to avoid allocating this IPv6 address to a device that expects to have a normal unicast address.

B.2.6. Addresses Used by Embedded-RP (RFC 3956)

Embedded-RP [RFC3956] reflects the concept of integrating the Rendezvous Point (RP) IPv6 address into the IPv6 multicast group address. Due to this embedding and the fact that the length of the IPv6 address AND the IPv6 multicast address are 128 bits, it is not possible to have the complete IPv6 address of the multicast RP embedded as such.

This results in a restriction of 15 possible RP-addresses per prefix that can be used with embedded-RP. The space assigned for the embedded-RP is based on the 4 low-order bits, while the remainder of the Rendezvous Interface ID (RIID) is set to all '0'. The format of the IPv6 multicast group address used by embedded-RP is as follows:

(IPv6-prefix (64 bits))(60 bits all '0')(RIID)

where: (RIID) = 4 bits.

This format implies that when selecting subnet prefixes longer than 64, and when the bits beyond the 64th bit are non-zero, the subnet cannot use embedded-RP.

In addition, it is discouraged to assign a matching embedded-RP IPv6 address to a device that is not a real Multicast Rendezvous Point, even though it would not generate major problems.

B.2.7. ISATAP Addresses

ISATAP [RFC5214] is an experimental automatic tunneling protocol used to provide IPv6 connectivity over an IPv4 campus or enterprise environment. In order to leverage the underlying IPv4 infrastructure, the IPv6 addresses are constructed in a special format.

An IPv6 ISATAP address has the IPv4 address embedded, based on a predefined structure policy that identifies them as an ISATAP address. The format is as follows:

[IPv6 Prefix (64 bits)][0000:5EFE][IPv4 address]

When using a subnet prefix length longer then 64 bits, it is good engineering practice to ensure that the portion of the IPv6 prefix from bit 65 to the end of the host-ID does not match with the well-known ISATAP [0000:5EFE] address when assigning an IPv6 address to a non-ISATAP interface.

Note that the definition of ISATAP does not support multicast.

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