Network Working Group
Request for Comments: 4213
Obsoletes: 2893
Category: Standards Track

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October 2005

Basic Transition Mechanisms for IPv6 Hosts and Routers

Status of This Memo

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Abstract

This document specifies IPv4 compatibility mechanisms that can be implemented by IPv6 hosts and routers. Two mechanisms are specified, dual stack and configured tunneling. Dual stack implies providing complete implementations of both versions of the Internet Protocol (IPv4 and IPv6), and configured tunneling provides a means to carry IPv6 packets over unmodified IPv4 routing infrastructures.

This document obsoletes RFC 2893.

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1. Introduction

The key to a successful IPv6 transition is compatibility with the large installed base of IPv4 hosts and routers. Maintaining compatibility with IPv4 while deploying IPv6 will streamline the task of transitioning the Internet to IPv6. This specification defines two mechanisms that IPv6 hosts and routers may implement in order to be compatible with IPv4 hosts and routers.

The mechanisms in this document are designed to be employed by IPv6 hosts and routers that need to interoperate with IPv4 hosts and utilize IPv4 routing infrastructures. We expect that most nodes in the Internet will need such compatibility for a long time to come, and perhaps even indefinitely.

The mechanisms specified here are:

- Dual IP layer (also known as dual stack): A technique for providing complete support for both Internet protocols -- IPv4 and IPv6 -- in hosts and routers.

- Configured tunneling of IPv6 over IPv4: A technique for establishing point-to-point tunnels by encapsulating IPv6 packets within IPv4 headers to carry them over IPv4 routing infrastructures.

The mechanisms defined here are intended to be the core of a "transition toolbox" -- a growing collection of techniques that implementations and users may employ to ease the transition. The tools may be used as needed. Implementations and sites decide which techniques are appropriate to their specific needs.

This document defines the basic set of transition mechanisms, but these are not the only tools available. Additional transition and compatibility mechanisms are specified in other documents.

1.1. Terminology

The following terms are used in this document:

Types of Nodes

IPv4-only node:

A host or router that implements only IPv4. An IPv4-only node does not understand IPv6. The installed base of IPv4 hosts and routers existing before the transition begins are IPv4-only nodes.

IPv6/IPv4 node:

A host or router that implements both IPv4 and IPv6.

IPv6-only node:

A host or router that implements IPv6 and does not implement IPv4. The operation of IPv6-only nodes is not addressed in this memo.

IPv6 node:

Any host or router that implements IPv6. IPv6/IPv4 and IPv6-only nodes are both IPv6 nodes.

IPv4 node:

Any host or router that implements IPv4. IPv6/IPv4 and IPv4-only nodes are both IPv4 nodes.

Techniques Used in the Transition

IPv6-over-IPv4 tunneling:

The technique of encapsulating IPv6 packets within IPv4 so that they can be carried across IPv4 routing infrastructures.

Configured tunneling:

IPv6-over-IPv4 tunneling where the IPv4 tunnel endpoint address(es) are determined by configuration information on tunnel endpoints. All tunnels are assumed to be bidirectional. The tunnel provides a (virtual) point-to-point link to the IPv6 layer, using the configured IPv4 addresses as the lower-layer endpoint addresses.

Other transition mechanisms, including other tunneling mechanisms, are outside the scope of this document.

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

2. Dual IP Layer Operation

The most straightforward way for IPv6 nodes to remain compatible with IPv4-only nodes is by providing a complete IPv4 implementation. IPv6 nodes that provide complete IPv4 and IPv6 implementations are called "IPv6/IPv4 nodes". IPv6/IPv4 nodes have the ability to send and receive both IPv4 and IPv6 packets. They can directly interoperate with IPv4 nodes using IPv4 packets, and also directly interoperate with IPv6 nodes using IPv6 packets.

Even though a node may be equipped to support both protocols, one or the other stack may be disabled for operational reasons. Here we use a rather loose notion of "stack". A stack being enabled has IP addresses assigned, but whether or not any particular application is available on the stacks is explicitly not defined. Thus, IPv6/IPv4 nodes may be operated in one of three modes:

- With their IPv4 stack enabled and their IPv6 stack disabled.

- With their IPv6 stack enabled and their IPv4 stack disabled.

- With both stacks enabled.

IPv6/IPv4 nodes with their IPv6 stack disabled will operate like IPv4-only nodes. Similarly, IPv6/IPv4 nodes with their IPv4 stacks

disabled will operate like IPv6-only nodes. IPv6/IPv4 nodes MAY provide a configuration switch to disable either their IPv4 or IPv6 stack.

The configured tunneling technique, which is described in Section 3, may or may not be used in addition to the dual IP layer operation.

2.1. Address Configuration

Because the nodes support both protocols, IPv6/IPv4 nodes may be configured with both IPv4 and IPv6 addresses. IPv6/IPv4 nodes use IPv4 mechanisms (e.g., DHCP) to acquire their IPv4 addresses, and IPv6 protocol mechanisms (e.g., stateless address autoconfiguration [RFC2462] and/or DHCPv6) to acquire their IPv6 addresses.

2.2. DNS

The Domain Naming System (DNS) is used in both IPv4 and IPv6 to map between hostnames and IP addresses. A new resource record type named "AAAA" has been defined for IPv6 addresses [RFC3596]. Since IPv6/IPv4 nodes must be able to interoperate directly with both IPv4 and IPv6 nodes, they must provide resolver libraries capable of dealing with IPv4 "A" records as well as IPv6 "AAAA" records. Note that the lookup of A versus AAAA records is independent of whether the DNS packets are carried in IPv4 or IPv6 packets and that there is no assumption that the DNS servers know the IPv4/IPv6 capabilities of the requesting node.

The issues and operational guidelines for using IPv6 with DNS are described at more length in other documents, e.g., [DNSOPV6].

DNS resolver libraries on IPv6/IPv4 nodes MUST be capable of handling both AAAA and A records. However, when a query locates an AAAA record holding an IPv6 address, and an A record holding an IPv4 address, the resolver library MAY order the results returned to the application in order to influence the version of IP packets used to communicate with that specific node -- IPv6 first, or IPv4 first.

The applications SHOULD be able to specify whether they want IPv4, IPv6, or both records [RFC3493]. That defines which address families the resolver looks up. If there is not an application choice, or if the application has requested both, the resolver library MUST NOT filter out any records.

Since most applications try the addresses in the order they are returned by the resolver, this can affect the IP version "preference" of applications.

The actual ordering mechanisms are out of scope of this memo. Address selection is described at more length in [RFC3484].

3. Configured Tunneling Mechanisms

In most deployment scenarios, the IPv6 routing infrastructure will be built up over time. While the IPv6 infrastructure is being deployed, the existing IPv4 routing infrastructure can remain functional and can be used to carry IPv6 traffic. Tunneling provides a way to utilize an existing IPv4 routing infrastructure to carry IPv6 traffic.

IPv6/IPv4 hosts and routers can tunnel IPv6 datagrams over regions of IPv4 routing topology by encapsulating them within IPv4 packets. Tunneling can be used in a variety of ways:

- Router-to-Router. IPv6/IPv4 routers interconnected by an IPv4 infrastructure can tunnel IPv6 packets between themselves. In this case, the tunnel spans one segment of the end-to-end path that the IPv6 packet takes.

- Host-to-Router. IPv6/IPv4 hosts can tunnel IPv6 packets to an intermediary IPv6/IPv4 router that is reachable via an IPv4 infrastructure. This type of tunnel spans the first segment of the packet's end-to-end path.

- Host-to-Host. IPv6/IPv4 hosts that are interconnected by an IPv4 infrastructure can tunnel IPv6 packets between themselves. In this case, the tunnel spans the entire end-to-end path that the packet takes.

- Router-to-Host. IPv6/IPv4 routers can tunnel IPv6 packets to their final destination IPv6/IPv4 host. This tunnel spans only the last segment of the end-to-end path.

Configured tunneling can be used in all of the above cases, but it is most likely to be used router-to-router due to the need to explicitly configure the tunneling endpoints.

The underlying mechanisms for tunneling are:

- The entry node of the tunnel (the encapsulator) creates an encapsulating IPv4 header and transmits the encapsulated packet.

- The exit node of the tunnel (the decapsulator) receives the encapsulated packet, reassembles the packet if needed, removes the IPv4 header, and processes the received IPv6 packet.

- The encapsulator may need to maintain soft-state information for each tunnel recording such parameters as the MTU of the tunnel in order to process IPv6 packets forwarded into the tunnel.

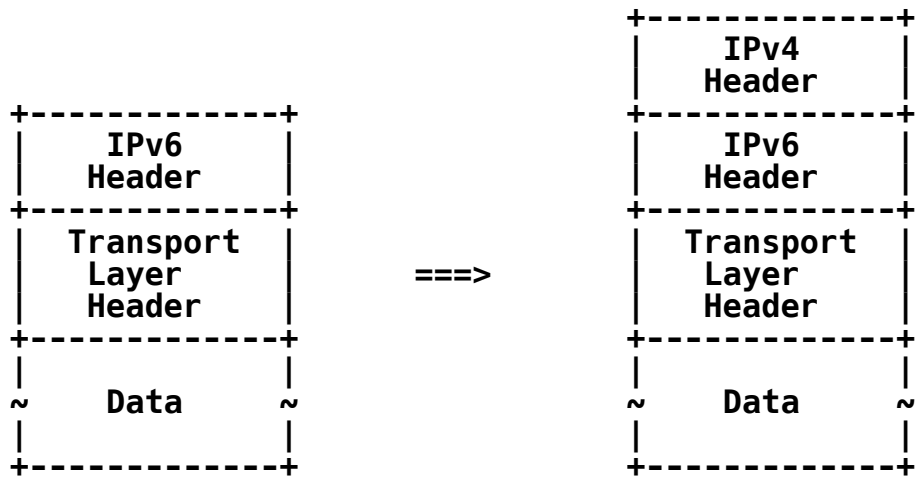
In configured tunneling, the tunnel endpoint addresses are determined in the encapsulator from configuration information stored for each tunnel. When an IPv6 packet is transmitted over a tunnel, the destination and source addresses for the encapsulating IPv4 header are set as described in Section 3.5.

The determination of which packets to tunnel is usually made by routing information on the encapsulator. This is usually done via a routing table, which directs packets based on their destination address using the prefix mask and match technique.

The decapsulator matches the received protocol-41 packets to the tunnels it has configured, and allows only the packets in which IPv4 source addresses match the tunnels configured on the decapsulator. Therefore, the operator must ensure that the tunnel's IPv4 address configuration is the same both at the encapsulator and the decapsulator.

3.1. Encapsulation

The encapsulation of an IPv6 datagram in IPv4 is shown below:



Encapsulating IPv6 in IPv4

In addition to adding an IPv4 header, the encapsulator also has to handle some more complex issues:

- Determine when to fragment and when to report an ICMPv6 "packet too big" error back to the source.

- How to reflect ICMPv4 errors from routers along the tunnel path back to the source as ICMPv6 errors.

Those issues are discussed in the following sections.

3.2. Tunnel MTU and Fragmentation

Naively, the encapsulator could view encapsulation as IPv6 using IPv4 as a link layer with a very large MTU (65535-20 bytes at most; 20 bytes "extra" are needed for the encapsulating IPv4 header). The encapsulator would only need to report ICMPv6 "packet too big" errors back to the source for packets that exceed this MTU. However, such a scheme would be inefficient or non-interoperable for three reasons and therefore MUST NOT be used:

1) It would result in more fragmentation than needed. IPv4 layer fragmentation should be avoided due to the performance problems caused by the loss unit being smaller than the retransmission unit [KM97].

2) Any IPv4 fragmentation occurring inside the tunnel, i.e., between the encapsulator and the decapsulator, would have to be reassembled at the tunnel endpoint. For tunnels that terminate at a router, this would require additional memory and other resources to reassemble the IPv4 fragments into a complete IPv6 packet before that packet could be forwarded.

3) The encapsulator has no way of knowing that the decapsulator is able to defragment such IPv4 packets (see Section 3.6 for details), and has no way of knowing that the decapsulator is able to handle such a large IPv6 Maximum Receive Unit (MRU).

Hence, the encapsulator MUST NOT treat the tunnel as an interface with an MTU of 64 kilobytes, but instead either use the fixed static MTU or OPTIONAL dynamic MTU determination based on the IPv4 path MTU to the tunnel endpoint.

If both the mechanisms are implemented, the decision of which to use SHOULD be configurable on a per-tunnel endpoint basis.

3.2.1. Static Tunnel MTU

A node using static tunnel MTU treats the tunnel interface as having a fixed-interface MTU. By default, the MTU MUST be between 1280 and 1480 bytes (inclusive), but it SHOULD be 1280 bytes. If the default is not 1280 bytes, the implementation MUST have a configuration knob that can be used to change the MTU value.

A node must be able to accept a fragmented IPv6 packet that, after reassembly, is as large as 1500 octets [RFC2460]. This memo also includes requirements (see Section 3.6) for the amount of IPv4 reassembly and IPv6 MRU that MUST be supported by all the decapsulators. These ensure correct interoperability with any fixed MTUs between 1280 and 1480 bytes.

A larger fixed MTU than supported by these requirements must not be configured unless it has been administratively ensured that the decapsulator can reassemble or receive packets of that size.

The selection of a good tunnel MTU depends on many factors, at least:

- Whether the IPv4 protocol-41 packets will be transported over media that may have a lower path MTU (e.g., IPv4 Virtual Private Networks); then picking too high a value might lead to IPv4 fragmentation.

- Whether the tunnel is used to transport IPv6 tunneled packets (e.g., a mobile node with an IPv6-in-IPv4 configured tunnel, and an IPv6-in-IPv6 tunnel interface); then picking too low a value might lead to IPv6 fragmentation.

If layered encapsulation is believed to be present, it may be prudent to consider supporting dynamic MTU determination instead as it is able to minimize fragmentation and optimize packet sizes.

When using the static tunnel MTU, the Don't Fragment bit MUST NOT be set in the encapsulating IPv4 header. As a result, the encapsulator should not receive any ICMPv4 "packet too big" messages as a result of the packets it has encapsulated.

3.2.2. Dynamic Tunnel MTU

The dynamic MTU determination is OPTIONAL. However, if it is implemented, it SHOULD have the behavior described in this document.

The fragmentation inside the tunnel can be reduced to a minimum by having the encapsulator track the IPv4 path MTU across the tunnel, using the IPv4 Path MTU Discovery Protocol [RFC1191] and recording

the resulting path MTU. The IPv6 layer in the encapsulator can then view a tunnel as a link layer with an MTU equal to the IPv4 path MTU, minus the size of the encapsulating IPv4 header.

Note that this does not eliminate IPv4 fragmentation in the case when the IPv4 path MTU would result in an IPv6 MTU less than 1280 bytes. (Any link layer used by IPv6 has to have an MTU of at least 1280 bytes [RFC2460].) In this case, the IPv6 layer has to "see" a link layer with an MTU of 1280 bytes and the encapsulator has to use IPv4 fragmentation in order to forward the 1280 byte IPv6 packets.

The encapsulator SHOULD employ the following algorithm to determine when to forward an IPv6 packet that is larger than the tunnel's path MTU using IPv4 fragmentation, and when to return an ICMPv6 "packet too big" message per [RFC1981]:

```
      if (IPv4 path MTU - 20) is less than 1280
              if packet is larger than 1280 bytes
                      Send ICMPv6 "packet too big" with MTU = 1280.
                      Drop packet.
              else
                      Encapsulate but do not set the Don't Fragment
                      flag in the IPv4 header.  The resulting IPv4
                      packet might be fragmented by the IPv4 layer
                      on the encapsulator or by some router along
                      the IPv4 path.
              endif
      else
              if packet is larger than (IPv4 path MTU - 20)
                      Send ICMPv6 "packet too big" with
                      MTU = (IPv4 path MTU - 20).
                      Drop packet.
              else
                      Encapsulate and set the Don't Fragment flag
                      in the IPv4 header.
              endif
      endif
```

Encapsulators that have a large number of tunnels may choose between dynamic versus static tunnel MTUs on a per-tunnel endpoint basis. In cases where the number of tunnels that any one node is using is large, it is helpful to observe that this state information can be cached and discarded when not in use.

Note that using dynamic tunnel MTU is subject to IPv4 path MTU blackholes should the ICMPv4 "packet too big" messages be dropped by firewalls or not generated by the routers [RFC1435, RFC2923].

3.3. Hop Limit

IPv6-over-IPv4 tunnels are modeled as "single-hop" from the IPv6 perspective. The tunnel is opaque to users of the network, and it is not detectable by network diagnostic tools such as traceroute.

The single-hop model is implemented by having the encapsulators and decapsulators process the IPv6 hop limit field as they would if they were forwarding a packet on to any other datalink. That is, they decrement the hop limit by 1 when forwarding an IPv6 packet. (The originating node and final destination do not decrement the hop limit.)

The TTL of the encapsulating IPv4 header is selected in an implementation-dependent manner. The current suggested value is published in the "Assigned Numbers" RFC [RFC3232][ASSIGNED]. Implementations MAY provide a mechanism to allow the administrator to configure the IPv4 TTL as the IP Tunnel MIB [RFC4087].

3.4. Handling ICMPv4 Errors

In response to encapsulated packets it has sent into the tunnel, the encapsulator might receive ICMPv4 error messages from IPv4 routers inside the tunnel. These packets are addressed to the encapsulator because it is the IPv4 source of the encapsulated packet.

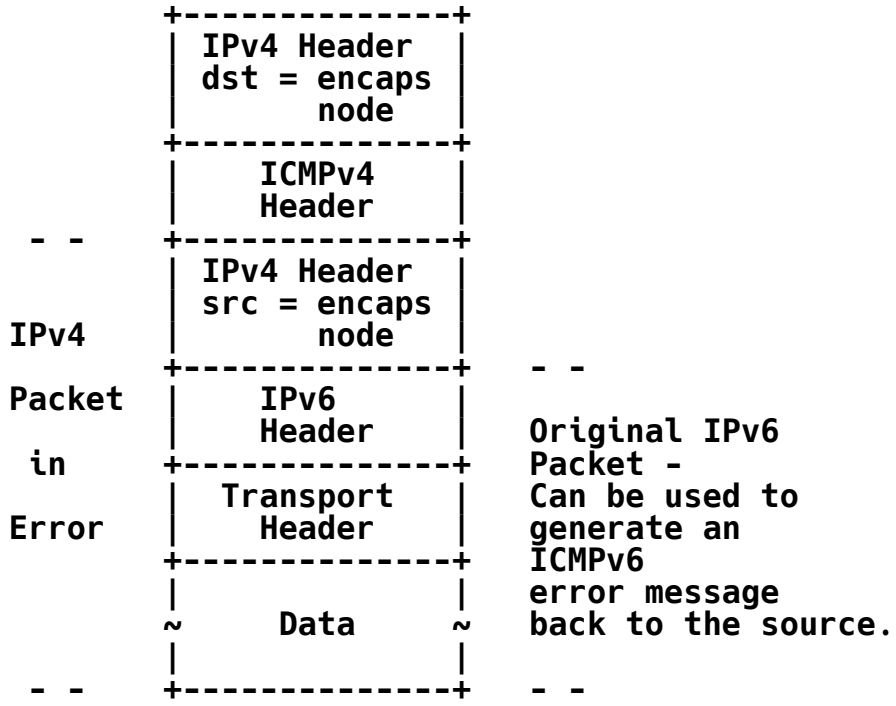
ICMPv4 error handling is only applicable to dynamic MTU determination, even though the functions could be used with static MTU tunnels as well.

The ICMPv4 "packet too big" error messages are handled according to IPv4 Path MTU Discovery [RFC1191] and the resulting path MTU is recorded in the IPv4 layer. The recorded path MTU is used by IPv6 to determine if an ICMPv6 "packet too big" error has to be generated as described in Section 3.2.2.

The handling of other types of ICMPv4 error messages depends on how much information is available from the encapsulated packet that caused the error.

Many older IPv4 routers return only 8 bytes of data beyond the IPv4 header of the packet in error, which is not enough to include the address fields of the IPv6 header. More modern IPv4 routers are likely to return enough data beyond the IPv4 header to include the entire IPv6 header and possibly even the data beyond that. See [RFC1812].

If sufficient data bytes from the offending packet are available, the encapsulator MAY extract the encapsulated IPv6 packet and use it to generate an ICMPv6 message directed back to the originating IPv6 node, as shown below:



ICMPv4 Error Message Returned to Encapsulating Node

When receiving ICMPv4 errors as above and the errors are not "packet too big", it would be useful to log the error as an error related to the tunnel. Also, if sufficient headers are available, then the originating node MAY send an ICMPv6 error of type "unreachable" with code "address unreachable" to the IPv6 source. (The "address unreachable" code is appropriate since, from the perspective of IPv6, the tunnel is a link and that code is used for link-specific errors [RFC2463]).

Note that when the IPv4 path MTU is exceeded, and sufficient bytes of payload associated with the ICMPv4 errors are not available, or ICMPv4 errors do not cause the generation of ICMPv6 errors in case there is enough payload, there will be at least two packet drops instead of at least one (the case of a single layer of MTU discovery). Consider a case where an IPv6 host is connected to an IPv4/IPv6 router, which is connected to a network where an ICMPv4 error about too big packet size is generated. First, the router needs to learn the tunnel (IPv4) MTU that causes at least one packet

loss, and then the host needs to learn the (IPv6) MTU from the router that causes at least one packet loss. Still, in all cases there can be more than one packet loss if there are multiple large packets in flight at the same time.

3.5. IPv4 Header Construction

When encapsulating an IPv6 packet in an IPv4 datagram, the IPv4 header fields are set as follows:

Version:

4

IP Header Length in 32-bit words:

5 (There are no IPv4 options in the encapsulating header.)

Type of Service:

0 unless otherwise specified. (See [RFC2983] and [RFC3168] Section 9.1 for issues relating to the Type-of-Service byte and tunneling.)

Total Length:

Payload length from IPv6 header plus length of IPv6 and IPv4 headers (i.e., IPv6 payload length plus a constant 60 bytes).

Identification:

Generated uniquely as for any IPv4 packet transmitted by the system.

Flags:

Set the Don't Fragment (DF) flag as specified in Section 3.2. Set the More Fragments (MF) bit as necessary if fragmenting.

Fragment Offset:

Set as necessary if fragmenting.

Time to Live:

Set in an implementation-specific manner, as described in Section 3.3.

Protocol:

41 (Assigned payload type number for IPv6).

Header Checksum:

Calculate the checksum of the IPv4 header [RFC791].

Source Address:

An IPv4 address of the encapsulator: either configured by the administrator or an address of the outgoing interface.

Destination Address:

IPv4 address of the tunnel endpoint.

When encapsulating the packets, the node must ensure that it will use the correct source address so that the packets are acceptable to the decapsulator as described in Section 3.6. Configuring the source address is appropriate particularly in cases in which automatic selection of source address may produce different results in a certain period of time. This is often the case with multiple addresses, and multiple interfaces, or when routes may change frequently. Therefore, it SHOULD be possible to administratively specify the source address of a tunnel.

3.6. Decapsulation

When an IPv6/IPv4 host or a router receives an IPv4 datagram that is addressed to one of its own IPv4 addresses or a joined multicast group address, and the value of the protocol field is 41, the packet is potentially a tunnel packet and needs to be verified to belong to one of the configured tunnel interfaces (by checking source/destination addresses), reassembled (if fragmented at the IPv4 level), and have the IPv4 header removed and the resulting IPv6 datagram be submitted to the IPv6 layer code on the node.

The decapsulator MUST verify that the tunnel source address is correct before further processing packets, to mitigate the problems with address spoofing (see Section 4). This check also applies to packets that are delivered to transport protocols on the decapsulator. This is done by verifying that the source address is the IPv4 address of the encapsulator, as configured on the decapsulator. Packets for which the IPv4 source address does not match MUST be discarded and an ICMP message SHOULD NOT be generated;

however, if the implementation normally sends an ICMP message when receiving an unknown protocol packet, such an error message MAY be sent (e.g., ICMPv4 Protocol 41 Unreachable).

A side effect of this address verification is that the node will silently discard packets with a wrong source address and packets that were received by the node but not directly addressed to it (e.g., broadcast addresses).

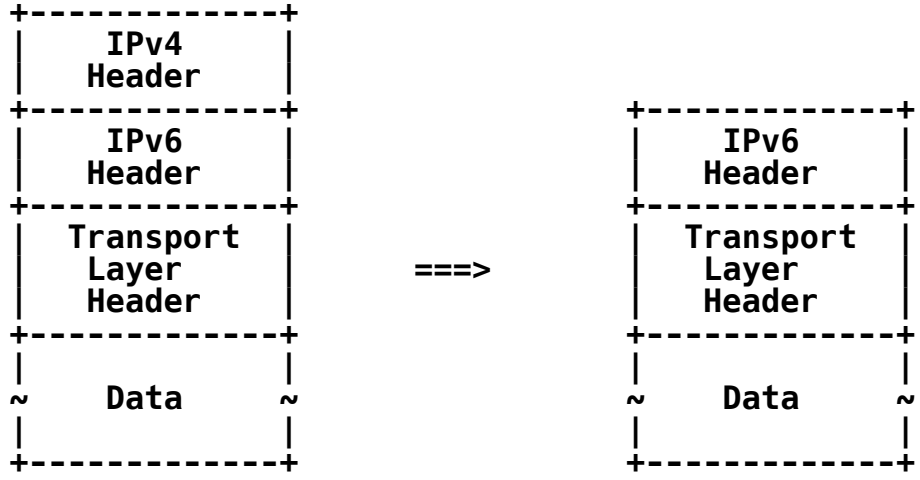
Independent of any other forms of IPv4 ingress filtering the administrator of the node may have configured, the implementation MAY perform ingress filtering, i.e., check that the packet is arriving from the interface in the direction of the route toward the tunnel end-point, similar to a Strict Reverse Path Forwarding (RPF) check [RFC3704]. As this may cause problems on tunnels that are routed through multiple links, it is RECOMMENDED that this check, if done, is disabled by default. The packets caught by this check SHOULD be discarded; an ICMP message SHOULD NOT be generated by default.

The decapsulator MUST be capable of having, on the tunnel interfaces, an IPv6 MRU of at least the maximum of 1500 bytes and the largest (IPv6) interface MTU on the decapsulator.

The decapsulator MUST be capable of reassembling an IPv4 packet that is (after the reassembly) the maximum of 1500 bytes and the largest (IPv4) interface MTU on the decapsulator. The 1500-byte number is a result of encapsulators that use the static MTU scheme in Section 3.2.1, while encapsulators that use the dynamic scheme in Section 3.2.2 can cause up to the largest interface MTU on the decapsulator to be received. (Note that it is strictly the interface MTU on the last IPv4 router *before* the decapsulator that matters, but for most links the MTU is the same between all neighbors.)

This reassembly limit allows dynamic tunnel MTU determination by the encapsulator to take advantage of larger IPv4 path MTUs. An implementation MAY have a configuration knob that can be used to set a larger value of the tunnel reassembly buffers than the above number, but it MUST NOT be set below the above number.

The decapsulation is shown below:



Decapsulating IPv6 from IPv4

The decapsulator performs IPv4 reassembly before decapsulating the IPv6 packet.

When decapsulating the packet, the IPv6 header is not modified. (However, see [RFC2983] and [RFC3168] section 9.1 for issues relating to the Type of Service byte and tunneling.) If the packet is subsequently forwarded, its hop limit is decremented by one.

The encapsulating IPv4 header is discarded, and the resulting packet is checked for validity when submitted to the IPv6 layer. When reconstructing the IPv6 packet, the length MUST be determined from the IPv6 payload length since the IPv4 packet might be padded (thus have a length that is larger than the IPv6 packet plus the IPv4 header being removed).

After the decapsulation, the node MUST silently discard a packet with an invalid IPv6 source address. The list of invalid source addresses SHOULD include at least:

- all multicast addresses (FF00::/8)

- the loopback address (::1)

- all the IPv4-compatible IPv6 addresses [RFC3513] (::/96), excluding the unspecified address for Duplicate Address Detection (::/128)

- all the IPv4-mapped IPv6 addresses (::ffff:0:0/96)

In addition, the node should be configured to perform ingress filtering [RFC2827][RFC3704] on the IPv6 source address, similar to on any of its interfaces, e.g.:

1) if the tunnel is toward the Internet, the node should be configured to check that the site's IPv6 prefixes are not used as the source addresses, or

2) if the tunnel is toward an edge network, the node should be configured to check that the source address belongs to that edge network.

The prefix lists in the former typically need to be manually configured; the latter could be verified automatically, e.g., by using a strict unicast RPF check, as long as an interface can be designated to be toward an edge.

It is RECOMMENDED that the implementations provide a single knob to make it easier to for the administrators to enable strict ingress filtering toward edge networks.

3.7. Link-Local Addresses

The configured tunnels are IPv6 interfaces (over the IPv4 "link layer") and thus MUST have link-local addresses. The link-local addresses are used by, e.g., routing protocols operating over the tunnels.

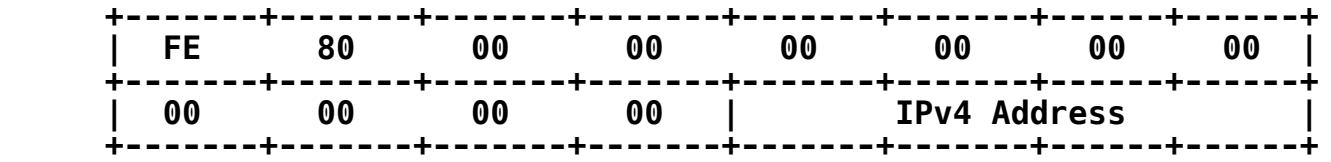
The interface identifier [RFC3513] for such an interface may be based on the 32-bit IPv4 address of an underlying interface, or formed using some other means, as long as it is unique from the other tunnel endpoint with a reasonably high probability.

Note that it may be desirable to form the link-local address in a fashion that minimizes the probability and the effect of having to renumber the link-local address in the event of a topology or hardware change.

If an IPv4 address is used for forming the IPv6 link-local address, the interface identifier is the IPv4 address, prepended by zeros. Note that the "Universal/Local" bit is zero, indicating that the interface identifier is not globally unique. The link-local address is formed by appending the interface identifier to the prefix FE80::/64.

When the host has more than one IPv4 address in use on the physical interface concerned, a choice of one of these IPv4 addresses is made

by the administrator or the implementation when forming the link-local address.



3.8. Neighbor Discovery over Tunnels

Configured tunnel implementations MUST at least accept and respond to the probe packets used by Neighbor Unreachability Detection (NUD) [RFC2461]. The implementations SHOULD also send NUD probe packets to detect when the configured tunnel fails at which point the implementation can use an alternate path to reach the destination. Note that Neighbor Discovery allows that the sending of NUD probes be omitted for router-to-router links if the routing protocol tracks bidirectional reachability.

For the purposes of Neighbor Discovery, the configured tunnels specified in this document are assumed to NOT have a link-layer address, even though the link-layer (IPv4) does have an address. This means that:

- the sender of Neighbor Discovery packets SHOULD NOT include Source Link Layer Address options or Target Link Layer Address options on the tunnel link.

- the receiver MUST, while otherwise processing the Neighbor Discovery packet, silently ignore the content of any Source Link Layer Address options or Target Link Layer Address options received on the tunnel link.

Not using link-layer address options is consistent with how Neighbor Discovery is used on other point-to-point links.

4. Threat Related to Source Address Spoofing

The specification above contains rules that apply tunnel source address verification in particular and ingress filtering [RFC2827][RFC3704] in general to packets before they are decapsulated. When IP-in-IP tunneling (independent of IP versions) is used, it is important that this not be used to bypass any ingress filtering in use for non-tunneled packets. Thus, the rules in this document are derived based on should ingress filtering be used for IPv4 and IPv6, the use of tunneling should not provide an easy way to circumvent the filtering.

In this case, without specific ingress filtering checks in the decapsulator, it would be possible for an attacker to inject a packet with:

- Outer IPv4 source: real IPv4 address of attacker
- Outer IPv4 destination: IPv4 address of decapsulator
- Inner IPv6 source: Alice, which is either the decapsulator or a node close to it
- Inner IPv6 destination: Bob

Even if all IPv4 routers between the attacker and the decapsulator implement IPv4 ingress filtering, and all IPv6 routers between the decapsulator and Bob implement IPv6 ingress filtering, the above spoofed packets will not be filtered out. As a result, Bob will receive a packet that looks like it was sent from Alice even though the sender was some unrelated node.

The solution to this is to have the decapsulator accept only encapsulated packets from the explicitly configured source address (i.e., the other end of the tunnel) as specified in Section 3.6. While this does not provide complete protection in the case ingress filtering has not been deployed, it does provide a significant increase in security. The issue and the remainder threats are discussed at more length in Security Considerations.

5. Security Considerations

Generic security considerations of using IPv6 are discussed in a separate document [V6SEC].

An implementation of tunneling needs to be aware that although a tunnel is a link (as defined in [RFC2460]), the threat model for a tunnel might be rather different than for other links, since the tunnel potentially includes all of the Internet.

Several mechanisms (e.g., Neighbor Discovery) depend on Hop Count being 255 and/or the addresses being link local for ensuring that a packet originated on-link, in a semi-trusted environment. Tunnels are more vulnerable to a breach of this assumption than physical links, as an attacker anywhere in the Internet can send an IPv6-in-IPv4 packet to the tunnel decapsulator, causing injection of an encapsulted IPv6 packet to the configured tunnel interface unless the decapsulation checks are able to discard packets injected in such a manner.

Therefore, this memo specifies that the decapsulators make these steps (as described in Section 3.6) to mitigate this threat:

- IPv4 source address of the packet MUST be the same as configured for the tunnel end-point;

- Independent of any IPv4 ingress filtering the administrator may have configured, the implementation MAY perform IPv4 ingress filtering to check that the IPv4 packets are received from an expected interface (but as this may cause some problems, it may be disabled by default);

- IPv6 packets with several, obviously invalid IPv6 source addresses received from the tunnel MUST be discarded (see Section 3.6 for details); and

- IPv6 ingress filtering should be performed (typically requiring configuration from the operator), to check that the tunneled IPv6 packets are received from an expected interface.

Especially the first verification is vital: to avoid this check, the attacker must be able to know the source of the tunnel (ranging from difficult to predictable) and be able to spoof it (easier).

If the remainder threats of tunnel source verification are considered to be significant, a tunneling scheme with authentication should be used instead, e.g., IPsec [RFC2401] (preferable) or Generic Routing Encapsulation with a pre-configured secret key [RFC2890]. As the configured tunnels are set up more or less manually, setting up the keying material is probably not a problem. However, setting up secure IPsec IPv6-in-IPv4 tunnels is described in another document [V64IPSEC].

If the tunneling is done inside an administrative domain, proper ingress filtering at the edge of the domain can also eliminate the threat from outside of the domain. Therefore, shorter tunnels are preferable to longer ones, possibly spanning the whole Internet.

In addition, an implementation MUST treat interfaces to different links as separate, e.g., to ensure that Neighbor Discovery packets arriving on one link do not affect other links. This is especially important for tunnel links.

When dropping packets due to failing to match the allowed IPv4 source addresses for a tunnel the node should not "acknowledge" the existence of a tunnel, otherwise this could be used to probe the acceptable tunnel endpoint addresses. For that reason, the specification says that such packets MUST be discarded, and an ICMP

error message SHOULD NOT be generated, unless the implementation normally sends ICMP destination unreachable messages for unknown protocols; in such a case, the same code MAY be sent. As should be obvious, not returning the same ICMP code if an error is returned for other protocols may hint that the IPv6 stack (or the protocol 41 tunneling processing) has been enabled -- the behaviour should be consistent on how the implementation otherwise behaves to be transparent to probing.

6. Acknowledgements

We would like to thank the members of the IPv6 working group, the Next Generation Transition (ngtrans) working group, and the v6ops working group for their many contributions and extensive review of this document. Special thanks are due to (in alphabetical order) Jim Bound, Ross Callon, Tim Chown, Alex Conta, Bob Hinden, Bill Manning, John Moy, Mohan Parthasarathy, Chirayu Patel, Pekka Savola, and Fred Templin for many helpful suggestions. Pekka Savola helped in editing the final revisions of the specification.

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8. Changes from RFC 2893

The motivation for the bulk of these changes are to simplify the document to only contain the mechanisms of wide-spread use.

RFC 2893 contains a mechanism called automatic tunneling. But a much more general mechanism is specified in RFC 3056 [RFC3056] which gives each node with a (global) IPv4 address a /48 IPv6 prefix i.e., enough for a whole site.

The following changes have been performed since RFC 2893:

- Removed references to A6 and retained AAAA.
- Removed automatic tunneling and use of IPv4-compatible addresses.
- Removed default Configured Tunnel using IPv4 "Anycast Address"
- Removed Source Address Selection section since this is now covered by another document ([RFC3484]).
- Removed brief mention of 6over4.

- Split into normative and non-normative references and other reference cleanup.

- Dropped "or equal" in if (IPv4 path MTU - 20) is less than or equal to 1280.

- Dropped this: However, IPv6 may be used in some environments where interoperability with IPv4 is not required. IPv6 nodes that are designed to be used in such environments need not use or even implement these mechanisms.

- Described Static MTU and Dynamic MTU cases separately; clarified that the dynamic path MTU mechanism is OPTIONAL but if it is implemented it should follow the rules in section 3.2.2.

- Specified Static MTU to default to a MTU of 1280 to 1480 bytes, and that this may be configurable. Discussed the issues with using Static MTU at more length.

- Specified minimal rules for IPv4 reassembly and IPv6 MRU to enhance interoperability and to minimize blacholes.

- Restated the "currently underway" language about Type-of-Service, and loosely point at [RFC2983] and [RFC3168].

- Fixed reference to Assigned Numbers to be to online version (with proper pointer to "Assigned Numbers is obsolete" RFC).

- Clarified text about ingress filtering e.g., that it applies to packet delivered to transport protocols on the decapsulator as well as packets being forwarded by the decapsulator, and how the decapsulator's checks help when IPv4 and IPv6 ingress filtering is in place.

- Removed unidirectional tunneling; assume all tunnels are bidirectional, between endpoint addresses (not nodes).

- Removed the guidelines for advertising addresses in DNS as slightly out of scope, referring to another document for the details.

- Removed the SHOULD requirement that the link-local addresses should be formed based on IPv4 addresses.

- Added a SHOULD for implementing a knob to be able to set the source address of the tunnel, and add discussion why this is useful.

- Added stronger wording for source address checks: both IPv4 and IPv6 source addresses MUST be checked, and RPF-like ingress filtering is optional.

- Rewrote security considerations to be more precise about the threats of tunneling.

- Added a note about considering using TTL=255 when encapsulating.

- Added more discussion in Section 3.2 why using an "infinite" IPv6 MTU leads to likely interoperability problems.

- Added an explicit requirement that if both MTU determination methods are used, choosing one should be possible on a per-tunnel basis.

- Clarified that ICMPv4 error handling is only applicable to dynamic MTU determination.

- Removed/clarified DNS record filtering; an API is a SHOULD and if it does not exist, MUST NOT filter anything. Decree ordering out of scope, but refer to RFC3484.

- Add a note that the destination IPv4 address could also be a multicast address.

- Make it RECOMMENDED to provide a toggle to perform strict ingress filtering on an interface.

- Generalize the text on the data in ICMPv4 messages.

- Made a lot of miscellaneous editorial cleanups.

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Acknowledgement

Funding for the RFC Editor function is currently provided by the Internet Society.