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Internet Protocol, Version 6 (IPv6) Specification

Abstract

This document specifies version 6 of the Internet Protocol (IPv6). It obsoletes RFC 2460.

Status of This Memo

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1. Introduction

IP version 6 (IPv6) is a new version of the Internet Protocol (IP), designed as the successor to IP version 4 (IPv4) [RFC791]. The changes from IPv4 to IPv6 fall primarily into the following categories:

- Expanded Addressing Capabilities

  IPv6 increases the IP address size from 32 bits to 128 bits, to support more levels of addressing hierarchy, a much greater number of addressable nodes, and simpler autoconfiguration of addresses. The scalability of multicast routing is improved by adding a "scope" field to multicast addresses. And a new type of address called an "anycast address" is defined; it is used to send a packet to any one of a group of nodes.

- Header Format Simplification

  Some IPv4 header fields have been dropped or made optional, to reduce the common-case processing cost of packet handling and to limit the bandwidth cost of the IPv6 header.

- Improved Support for Extensions and Options

  Changes in the way IP header options are encoded allows for more efficient forwarding, less stringent limits on the length of options, and greater flexibility for introducing new options in the future.

- Flow Labeling Capability

  A new capability is added to enable the labeling of sequences of packets that the sender requests to be treated in the network as a single flow.

- Authentication and Privacy Capabilities

  Extensions to support authentication, data integrity, and (optional) data confidentiality are specified for IPv6.

This document specifies the basic IPv6 header and the initially defined IPv6 extension headers and options. It also discusses packet size issues, the semantics of flow labels and traffic classes, and the effects of IPv6 on upper-layer protocols. The format and semantics of IPv6 addresses are specified separately in [RFC4291]. The IPv6 version of ICMP, which all IPv6 implementations are required to include, is specified in [RFC4443].

The data transmission order for IPv6 is the same as for IPv4 as defined in Appendix B of [RFC791].

Note: As this document obsoletes [RFC2460], any document referenced in this document that includes pointers to RFC 2460 should be interpreted as referencing this document.

2. Terminology

node	a device that implements IPv6.
router	a node that forwards IPv6 packets not explicitly addressed to itself. (See Note below.)
host	any node that is not a router. (See Note below.)
upper layer	a protocol layer immediately above IPv6. Examples are transport protocols such as TCP and UDP, control protocols such as ICMP, routing protocols such as OSPF, and internet-layer or lower-layer protocols being "tunneled" over (i.e., encapsulated in) IPv6 such as Internetwork Packet Exchange (IPX), AppleTalk, or IPv6 itself.
link	a communication facility or medium over which nodes can communicate at the link layer, i.e., the layer immediately below IPv6. Examples are Ethernets (simple or bridged); PPP links; X.25, Frame Relay, or ATM networks; and internet-layer or higher-layer "tunnels", such as tunnels over IPv4 or IPv6 itself.
neighbors	nodes attached to the same link.
interface	a node's attachment to a link.
address	an IPv6-layer identifier for an interface or a set of interfaces.
packet	an IPv6 header plus payload.
link MTU	the maximum transmission unit, i.e., maximum packet size in octets, that can be conveyed over a link.
path MTU	the minimum link MTU of all the links in a path between a source node and a destination node.

Note: it is possible for a device with multiple interfaces to be configured to forward non-self-destined packets arriving from some set (fewer than all) of its interfaces and to discard non-self-destined packets arriving from its other interfaces. Such a device must obey the protocol requirements for routers when receiving packets from, and interacting with neighbors over, the former (forwarding) interfaces. It must obey the protocol requirements for hosts when receiving packets from, and interacting with neighbors over, the latter (non-forwarding) interfaces.

3. IPv6 Header Format

```
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |Version| Traffic Class |           Flow Label                  |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |         Payload Length        |  Next Header  |   Hop Limit   |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                                                               |
   +                                                               +
   |                                                               |
   +                         Source Address                        +
   |                                                               |
   +                                                               +
   |                                                               |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                                                               |
   +                                                               +
   |                                                               |
   +                      Destination Address                      +
   |                                                               |
   +                                                               +
   |                                                               |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Version	4-bit Internet Protocol version number = 6.
Traffic Class	8-bit Traffic Class field. See Section 7.
Flow Label	20-bit flow label. See Section 6.
Payload Length	16-bit unsigned integer. Length of the IPv6 payload, i.e., the rest of the packet following this IPv6 header, in octets. (Note that any extension headers (see Section 4) present are considered part of the payload, i.e., included in the length count.)

Next Header	8-bit selector. Identifies the type of header immediately following the IPv6 header. Uses the same values as the IPv4 Protocol field [IANA-PN].
Hop Limit	8-bit unsigned integer. Decremented by 1 by each node that forwards the packet. When forwarding, the packet is discarded if Hop Limit was zero when received or is decremented to zero. A node that is the destination of a packet should not discard a packet with Hop Limit equal to zero; it should process the packet normally.
Source Address	128-bit address of the originator of the packet. See [RFC4291].
Destination Address	128-bit address of the intended recipient of the packet (possibly not the ultimate recipient, if a Routing header is present). See [RFC4291] and Section 4.4.

4. IPv6 Extension Headers

In IPv6, optional internet-layer information is encoded in separate headers that may be placed between the IPv6 header and the upper-layer header in a packet. There is a small number of such extension headers, each one identified by a distinct Next Header value.

Extension headers are numbered from IANA IP Protocol Numbers [IANA-PN], the same values used for IPv4 and IPv6. When processing a sequence of Next Header values in a packet, the first one that is not an extension header [IANA-EH] indicates that the next item in the packet is the corresponding upper-layer header. A special "No Next Header" value is used if there is no upper-layer header.

As illustrated in these examples, an IPv6 packet may carry zero, one, or more extension headers, each identified by the Next Header field of the preceding header:

```
   +---------------+------------------------
   |  IPv6 header  | TCP header + data
   |               |
   | Next Header = |
   |      TCP      |
   +---------------+------------------------

   +---------------+----------------+------------------------
   |  IPv6 header  | Routing header | TCP header + data
   |               |                |
   | Next Header = |  Next Header = |
   |    Routing    |      TCP       |
   +---------------+----------------+------------------------

   +---------------+----------------+-----------------+-----------------
   |  IPv6 header  | Routing header | Fragment header | fragment of TCP
   |               |                |                 |  header + data
   | Next Header = |  Next Header = |  Next Header =  |
   |    Routing    |    Fragment    |       TCP       |
   +---------------+----------------+-----------------+-----------------
```

Extension headers (except for the Hop-by-Hop Options header) are not processed, inserted, or deleted by any node along a packet's delivery path, until the packet reaches the node (or each of the set of nodes, in the case of multicast) identified in the Destination Address field of the IPv6 header.

The Hop-by-Hop Options header is not inserted or deleted, but may be examined or processed by any node along a packet's delivery path, until the packet reaches the node (or each of the set of nodes, in the case of multicast) identified in the Destination Address field of the IPv6 header. The Hop-by-Hop Options header, when present, must immediately follow the IPv6 header. Its presence is indicated by the value zero in the Next Header field of the IPv6 header.

NOTE: While [RFC2460] required that all nodes must examine and process the Hop-by-Hop Options header, it is now expected that nodes along a packet's delivery path only examine and process the Hop-by-Hop Options header if explicitly configured to do so.

At the destination node, normal demultiplexing on the Next Header field of the IPv6 header invokes the module to process the first extension header, or the upper-layer header if no extension header is present. The contents and semantics of each extension header determine whether or not to proceed to the next header. Therefore, extension headers must be processed strictly in the order they appear in the packet; a receiver must not, for example, scan through a packet looking for a particular kind of extension header and process that header prior to processing all preceding ones.

If, as a result of processing a header, the destination node is required to proceed to the next header but the Next Header value in the current header is unrecognized by the node, it should discard the packet and send an ICMP Parameter Problem message to the source of the packet, with an ICMP Code value of 1 ("unrecognized Next Header type encountered") and the ICMP Pointer field containing the offset of the unrecognized value within the original packet. The same action should be taken if a node encounters a Next Header value of zero in any header other than an IPv6 header.

Each extension header is an integer multiple of 8 octets long, in order to retain 8-octet alignment for subsequent headers. Multi-octet fields within each extension header are aligned on their natural boundaries, i.e., fields of width n octets are placed at an integer multiple of n octets from the start of the header, for n = 1, 2, 4, or 8.

A full implementation of IPv6 includes implementation of the following extension headers:

```
Hop-by-Hop Options
Fragment
Destination Options
Routing
Authentication
Encapsulating Security Payload
```

The first four are specified in this document; the last two are specified in [RFC4302] and [RFC4303], respectively. The current list of IPv6 extension headers can be found at [IANA-EH].

4.1. Extension Header Order

When more than one extension header is used in the same packet, it is recommended that those headers appear in the following order:

```
IPv6 header
Hop-by-Hop Options header
Destination Options header (note 1)
Routing header
Fragment header
Authentication header (note 2)
Encapsulating Security Payload header (note 2)
Destination Options header (note 3)
Upper-Layer header
```

note 1: for options to be processed by the first destination that appears in the IPv6 Destination Address field plus subsequent destinations listed in the Routing header.

note 2: additional recommendations regarding the relative order of the Authentication and Encapsulating Security Payload headers are given in [RFC4303].

note 3: for options to be processed only by the final destination of the packet.

Each extension header should occur at most once, except for the Destination Options header, which should occur at most twice (once before a Routing header and once before the upper-layer header).

If the upper-layer header is another IPv6 header (in the case of IPv6 being tunneled over or encapsulated in IPv6), it may be followed by its own extension headers, which are separately subject to the same ordering recommendations.

If and when other extension headers are defined, their ordering constraints relative to the above listed headers must be specified.

IPv6 nodes must accept and attempt to process extension headers in any order and occurring any number of times in the same packet, except for the Hop-by-Hop Options header, which is restricted to appear immediately after an IPv6 header only. Nonetheless, it is strongly advised that sources of IPv6 packets adhere to the above recommended order until and unless subsequent specifications revise that recommendation.

4.2. Options

Two of the currently defined extension headers specified in this document -- the Hop-by-Hop Options header and the Destination Options header -- carry a variable number of "options" that are type-length-value (TLV) encoded in the following format:

```
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+- - - - - - - - -
|  Option Type  |  Opt Data Len |  Option Data
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+- - - - - - - - -
```

Option Type	8-bit identifier of the type of option.
Opt Data Len	8-bit unsigned integer. Length of the Option Data field of this option, in octets.
Option Data	Variable-length field. Option-Type-specific data.

The sequence of options within a header must be processed strictly in the order they appear in the header; a receiver must not, for example, scan through the header looking for a particular kind of option and process that option prior to processing all preceding ones.

The Option Type identifiers are internally encoded such that their highest-order 2 bits specify the action that must be taken if the processing IPv6 node does not recognize the Option Type:

00 - skip over this option and continue processing the header.

01 - discard the packet.

10 - discard the packet and, regardless of whether or not the packet's Destination Address was a multicast address, send an ICMP Parameter Problem, Code 2, message to the packet's Source Address, pointing to the unrecognized Option Type.

11 - discard the packet and, only if the packet's Destination Address was not a multicast address, send an ICMP Parameter Problem, Code 2, message to the packet's Source Address, pointing to the unrecognized Option Type.

The third-highest-order bit of the Option Type specifies whether or not the Option Data of that option can change en route to the packet's final destination. When an Authentication header is present in the packet, for any option whose data may change en route, its entire Option Data field must be treated as zero-valued octets when computing or verifying the packet's authenticating value.

0 - Option Data does not change en route

1 - Option Data may change en route

The three high-order bits described above are to be treated as part of the Option Type, not independent of the Option Type. That is, a particular option is identified by a full 8-bit Option Type, not just the low-order 5 bits of an Option Type.

The same Option Type numbering space is used for both the Hop-by-Hop Options header and the Destination Options header. However, the specification of a particular option may restrict its use to only one of those two headers.

Individual options may have specific alignment requirements, to ensure that multi-octet values within Option Data fields fall on natural boundaries. The alignment requirement of an option is specified using the notation xn+y, meaning the Option Type must appear at an integer multiple of x octets from the start of the header, plus y octets. For example:

```
   2n     means any 2-octet offset from the start of the header.
   8n+2   means any 8-octet offset from the start of the header, plus
          2 octets.
```

There are two padding options that are used when necessary to align subsequent options and to pad out the containing header to a multiple of 8 octets in length. These padding options must be recognized by all IPv6 implementations:

Pad1 option (alignment requirement: none)

```
   +-+-+-+-+-+-+-+-+
   |       0       |
   +-+-+-+-+-+-+-+-+
```

NOTE! the format of the Pad1 option is a special case -- it does not have length and value fields.

The Pad1 option is used to insert 1 octet of padding into the Options area of a header. If more than one octet of padding is required, the PadN option, described next, should be used, rather than multiple Pad1 options.

PadN option (alignment requirement: none)

```
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+- - - - - - - - -
   |       1       |  Opt Data Len |  Option Data
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+- - - - - - - - -
```

The PadN option is used to insert two or more octets of padding into the Options area of a header. For N octets of padding, the Opt Data Len field contains the value N-2, and the Option Data consists of N-2 zero-valued octets.

Appendix A contains formatting guidelines for designing new options.

4.3. Hop-by-Hop Options Header

The Hop-by-Hop Options header is used to carry optional information that may be examined and processed by every node along a packet's delivery path. The Hop-by-Hop Options header is identified by a Next Header value of 0 in the IPv6 header and has the following format:

```
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |  Next Header  |  Hdr Ext Len  |                               |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+                               +
 |                                                               |
 .                                                               .
 .                            Options                            .
 .                                                               .
 |                                                               |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Next Header	8-bit selector. Identifies the type of header immediately following the Hop-by-Hop Options header. Uses the same values as the IPv4 Protocol field [IANA-PN].
Hdr Ext Len	8-bit unsigned integer. Length of the Hop-by-Hop Options header in 8-octet units, not including the first 8 octets.
Options	Variable-length field, of length such that the complete Hop-by-Hop Options header is an integer multiple of 8 octets long. Contains one or more TLV-encoded options, as described in Section 4.2.

The only hop-by-hop options defined in this document are the Pad1 and PadN options specified in Section 4.2.

4.4. Routing Header

The Routing header is used by an IPv6 source to list one or more intermediate nodes to be "visited" on the way to a packet's destination. This function is very similar to IPv4's Loose Source and Record Route option. The Routing header is identified by a Next Header value of 43 in the immediately preceding header and has the following format:

```
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    |  Next Header  |  Hdr Ext Len  |  Routing Type | Segments Left |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    |                                                               |
    .                                                               .
    .                       type-specific data                      .
    .                                                               .
    |                                                               |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Next Header	8-bit selector. Identifies the type of header immediately following the Routing header. Uses the same values as the IPv4 Protocol field [IANA-PN].
Hdr Ext Len	8-bit unsigned integer. Length of the Routing header in 8-octet units, not including the first 8 octets.
Routing Type	8-bit identifier of a particular Routing header variant.
Segments Left	8-bit unsigned integer. Number of route segments remaining, i.e., number of explicitly listed intermediate nodes still to be visited before reaching the final destination.
type-specific data	Variable-length field, of format determined by the Routing Type, and of length such that the complete Routing header is an integer multiple of 8 octets long.

If, while processing a received packet, a node encounters a Routing header with an unrecognized Routing Type value, the required behavior of the node depends on the value of the Segments Left field, as follows:

If Segments Left is zero, the node must ignore the Routing header and proceed to process the next header in the packet, whose type is identified by the Next Header field in the Routing header.

If Segments Left is non-zero, the node must discard the packet and send an ICMP Parameter Problem, Code 0, message to the packet's Source Address, pointing to the unrecognized Routing Type.

If, after processing a Routing header of a received packet, an intermediate node determines that the packet is to be forwarded onto a link whose link MTU is less than the size of the packet, the node must discard the packet and send an ICMP Packet Too Big message to the packet's Source Address.

The currently defined IPv6 Routing Headers and their status can be found at [IANA-RH]. Allocation guidelines for IPv6 Routing Headers can be found in [RFC5871].

4.5. Fragment Header

The Fragment header is used by an IPv6 source to send a packet larger than would fit in the path MTU to its destination. (Note: unlike IPv4, fragmentation in IPv6 is performed only by source nodes, not by routers along a packet's delivery path -- see Section 5.) The Fragment header is identified by a Next Header value of 44 in the immediately preceding header and has the following format:

```
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Next Header  |   Reserved    |      Fragment Offset    |Res|M|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                         Identification                        |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Next Header	8-bit selector. Identifies the initial header type of the Fragmentable Part of the original packet (defined below). Uses the same values as the IPv4 Protocol field [IANA-PN].
Reserved	8-bit reserved field. Initialized to zero for transmission; ignored on reception.

Fragment Offset	13-bit unsigned integer. The offset, in 8-octet units, of the data following this header, relative to the start of the Fragmentable Part of the original packet.
Res	2-bit reserved field. Initialized to zero for transmission; ignored on reception.
M flag	1 = more fragments; 0 = last fragment.
Identification	32 bits. See description below.

In order to send a packet that is too large to fit in the MTU of the path to its destination, a source node may divide the packet into fragments and send each fragment as a separate packet, to be reassembled at the receiver.

For every packet that is to be fragmented, the source node generates an Identification value. The Identification must be different than that of any other fragmented packet sent recently* with the same Source Address and Destination Address. If a Routing header is present, the Destination Address of concern is that of the final destination.

* "recently" means within the maximum likely lifetime of a packet, including transit time from source to destination and time spent awaiting reassembly with other fragments of the same packet. However, it is not required that a source node knows the maximum packet lifetime. Rather, it is assumed that the requirement can be met by implementing an algorithm that results in a low identification reuse frequency. Examples of algorithms that can meet this requirement are described in [RFC7739].

The initial, large, unfragmented packet is referred to as the "original packet", and it is considered to consist of three parts, as illustrated:

original packet:

```
+------------------+-------------------------+---//----------------+
|  Per-Fragment    | Extension & Upper-Layer |   Fragmentable      |
|    Headers       |        Headers          |      Part           |
+------------------+-------------------------+---//----------------+
```

   The Per-Fragment headers must consist of the IPv6 header plus any extension headers that must be processed by nodes en route to the destination, that is, all headers up to and including the Routing header if present, else the Hop-by-Hop Options header if present, else no extension headers.

   The Extension headers are all other extension headers that are not included in the Per-Fragment headers part of the packet. For this purpose, the Encapsulating Security Payload (ESP) is not considered an extension header. The Upper-Layer header is the first upper-layer header that is not an IPv6 extension header. Examples of upper-layer headers include TCP, UDP, IPv4, IPv6, ICMPv6, and as noted ESP.

   The Fragmentable Part consists of the rest of the packet after the upper-layer header or after any header (i.e., initial IPv6 header or extension header) that contains a Next Header value of No Next Header.

The Fragmentable Part of the original packet is divided into fragments. The lengths of the fragments must be chosen such that the resulting fragment packets fit within the MTU of the path to the packet's destination(s). Each complete fragment, except possibly the last ("rightmost") one, is an integer multiple of 8 octets long.

The fragments are transmitted in separate "fragment packets" as illustrated:

original packet:

```
+------------------+-----------------+--------+--------+-//-+--------+
|  Per-Fragment    |Ext & Upper-Layer|  first | second |    |  last  |
|    Headers       |    Headers      |fragment|fragment|....|fragment|
+------------------+-----------------+--------+--------+-//-+--------+
```

fragment packets:

```
+------------------+---------+-------------------+----------+
|  Per-Fragment    |Fragment | Ext & Upper-Layer |  first   |
|    Headers       | Header  |   Headers         | fragment |
+------------------+---------+-------------------+----------+

+------------------+--------+-------------------------------+
|  Per-Fragment    |Fragment|    second                     |
|    Headers       | Header |   fragment                    |
+------------------+--------+-------------------------------+
                      o
                      o
                      o
+------------------+--------+----------+
|  Per-Fragment    |Fragment|    last  |
|    Headers       | Header | fragment |
+------------------+--------+----------+
```

The first fragment packet is composed of:

(1) The Per-Fragment headers of the original packet, with the Payload Length of the original IPv6 header changed to contain the length of this fragment packet only (excluding the length of the IPv6 header itself), and the Next Header field of the last header of the Per-Fragment headers changed to 44.

(2) A Fragment header containing:

The Next Header value that identifies the first header after the Per-Fragment headers of the original packet.

A Fragment Offset containing the offset of the fragment, in 8-octet units, relative to the start of the Fragmentable Part of the original packet. The Fragment Offset of the first ("leftmost") fragment is 0.

An M flag value of 1 as this is the first fragment.

The Identification value generated for the original packet.

(3) Extension headers, if any, and the Upper-Layer header. These headers must be in the first fragment. Note: This restricts the size of the headers through the Upper-Layer header to the MTU of the path to the packet's destinations(s).

(4) The first fragment.

The subsequent fragment packets are composed of:

(1) The Per-Fragment headers of the original packet, with the Payload Length of the original IPv6 header changed to contain the length of this fragment packet only (excluding the length of the IPv6 header itself), and the Next Header field of the last header of the Per-Fragment headers changed to 44.

(2) A Fragment header containing:

The Next Header value that identifies the first header after the Per-Fragment headers of the original packet.

A Fragment Offset containing the offset of the fragment, in 8-octet units, relative to the start of the Fragmentable Part of the original packet.

An M flag value of 0 if the fragment is the last ("rightmost") one, else an M flag value of 1.

The Identification value generated for the original packet.

(3) The fragment itself.

Fragments must not be created that overlap with any other fragments created from the original packet.

At the destination, fragment packets are reassembled into their original, unfragmented form, as illustrated:

reassembled original packet:

```
+---------------+-----------------+---------+--------+-//--+--------+
| Per-Fragment  |Ext & Upper-Layer|  first  | second |     | last   |
|    Headers    |     Headers     |frag data|fragment|.....|fragment|
+---------------+-----------------+---------+--------+-//--+--------+
```

The following rules govern reassembly:

An original packet is reassembled only from fragment packets that have the same Source Address, Destination Address, and Fragment Identification.

The Per-Fragment headers of the reassembled packet consists of all headers up to, but not including, the Fragment header of the first fragment packet (that is, the packet whose Fragment Offset is zero), with the following two changes:

The Next Header field of the last header of the Per-Fragment headers is obtained from the Next Header field of the first fragment's Fragment header.

The Payload Length of the reassembled packet is computed from the length of the Per-Fragment headers and the length and offset of the last fragment. For example, a formula for computing the Payload Length of the reassembled original packet is:

```
PL.orig = PL.first - FL.first - 8 + (8 * FO.last) + FL.last

where
PL.orig  =  Payload Length field of reassembled packet.
PL.first =  Payload Length field of first fragment packet.
FL.first =  length of fragment following Fragment header of
            first fragment packet.
FO.last  =  Fragment Offset field of Fragment header of last
            fragment packet.
FL.last  =  length of fragment following Fragment header of
            last fragment packet.
```

The Fragmentable Part of the reassembled packet is constructed from the fragments following the Fragment headers in each of the fragment packets. The length of each fragment is computed by subtracting from the packet's Payload Length the length of the headers between the IPv6 header and fragment itself; its relative position in Fragmentable Part is computed from its Fragment Offset value.

The Fragment header is not present in the final, reassembled packet.

If the fragment is a whole datagram (that is, both the Fragment Offset field and the M flag are zero), then it does not need any further reassembly and should be processed as a fully reassembled packet (i.e., updating Next Header, adjust Payload Length, removing the Fragment header, etc.). Any other fragments that match this packet (i.e., the same IPv6 Source Address, IPv6 Destination Address, and Fragment Identification) should be processed independently.

The following error conditions may arise when reassembling fragmented packets:

- If insufficient fragments are received to complete reassembly of a packet within 60 seconds of the reception of the first-arriving fragment of that packet, reassembly of that packet must be abandoned and all the fragments that have been received for that packet must be discarded. If the first fragment (i.e., the one with a Fragment Offset of zero) has been received, an ICMP Time Exceeded -- Fragment Reassembly Time Exceeded message should be sent to the source of that fragment.

- If the length of a fragment, as derived from the fragment packet's Payload Length field, is not a multiple of 8 octets and the M flag of that fragment is 1, then that fragment must be discarded and an ICMP Parameter Problem, Code 0, message should be sent to the source of the fragment, pointing to the Payload Length field of the fragment packet.

- If the length and offset of a fragment are such that the Payload Length of the packet reassembled from that fragment would exceed 65,535 octets, then that fragment must be discarded and an ICMP Parameter Problem, Code 0, message should be sent to the source of the fragment, pointing to the Fragment Offset field of the fragment packet.

- If the first fragment does not include all headers through an Upper-Layer header, then that fragment should be discarded and an ICMP Parameter Problem, Code 3, message should be sent to the source of the fragment, with the Pointer field set to zero.

- If any of the fragments being reassembled overlap with any other fragments being reassembled for the same packet, reassembly of that packet must be abandoned and all the fragments that have been received for that packet must be discarded, and no ICMP error messages should be sent.

  It should be noted that fragments may be duplicated in the network. Instead of treating these exact duplicate fragments as overlapping fragments, an implementation may choose to detect this case and drop exact duplicate fragments while keeping the other fragments belonging to the same packet.

The following conditions are not expected to occur frequently but are not considered errors if they do:

The number and content of the headers preceding the Fragment header of different fragments of the same original packet may differ. Whatever headers are present, preceding the Fragment header in each fragment packet, are processed when the packets arrive, prior to queueing the fragments for reassembly. Only those headers in the Offset zero fragment packet are retained in the reassembled packet.

The Next Header values in the Fragment headers of different fragments of the same original packet may differ. Only the value from the Offset zero fragment packet is used for reassembly.

Other fields in the IPv6 header may also vary across the fragments being reassembled. Specifications that use these fields may provide additional instructions if the basic mechanism of using the values from the Offset zero fragment is not sufficient. For example, Section 5.3 of [RFC3168] describes how to combine the Explicit Congestion Notification (ECN) bits from different fragments to derive the ECN bits of the reassembled packet.

4.6. Destination Options Header

The Destination Options header is used to carry optional information that need be examined only by a packet's destination node(s). The Destination Options header is identified by a Next Header value of 60 in the immediately preceding header and has the following format:

```
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    |  Next Header  |  Hdr Ext Len  |                               |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+                               +
    |                                                               |
    .                                                               .
    .                            Options                            .
    .                                                               .
    |                                                               |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Next Header	8-bit selector. Identifies the type of header immediately following the Destination Options header. Uses the same values as the IPv4 Protocol field [IANA-PN].
Hdr Ext Len	8-bit unsigned integer. Length of the Destination Options header in 8-octet units, not including the first 8 octets.
Options	Variable-length field, of length such that the complete Destination Options header is an integer multiple of 8 octets long. Contains one or more TLV-encoded options, as described in Section 4.2.

The only destination options defined in this document are the Pad1 and PadN options specified in Section 4.2.

Note that there are two possible ways to encode optional destination information in an IPv6 packet: either as an option in the Destination Options header or as a separate extension header. The Fragment header and the Authentication header are examples of the latter approach. Which approach can be used depends on what action is desired of a destination node that does not understand the optional information:

o If the desired action is for the destination node to discard the packet and, only if the packet's Destination Address is not a multicast address, send an ICMP Unrecognized Type message to the packet's Source Address, then the information may be encoded either as a separate header or as an option in the

Destination Options header whose Option Type has the value 11 in its highest-order 2 bits. The choice may depend on such factors as which takes fewer octets, or which yields better alignment or more efficient parsing.

- If any other action is desired, the information must be encoded as an option in the Destination Options header whose Option Type has the value 00, 01, or 10 in its highest-order 2 bits, specifying the desired action (see Section 4.2).

4.7. No Next Header

The value 59 in the Next Header field of an IPv6 header or any extension header indicates that there is nothing following that header. If the Payload Length field of the IPv6 header indicates the presence of octets past the end of a header whose Next Header field contains 59, those octets must be ignored and passed on unchanged if the packet is forwarded.

4.8. Defining New Extension Headers and Options

Defining new IPv6 extension headers is not recommended, unless there are no existing IPv6 extension headers that can be used by specifying a new option for that IPv6 extension header. A proposal to specify a new IPv6 extension header must include a detailed technical explanation of why an existing IPv6 extension header can not be used for the desired new function. See [RFC6564] for additional background information.

Note: New extension headers that require hop-by-hop behavior must not be defined because, as specified in Section 4 of this document, the only extension header that has hop-by-hop behavior is the Hop-by-Hop Options header.

New hop-by-hop options are not recommended because nodes may be configured to ignore the Hop-by-Hop Options header, drop packets containing a Hop-by-Hop Options header, or assign packets containing a Hop-by-Hop Options header to a slow processing path. Designers considering defining new hop-by-hop options need to be aware of this likely behavior. There has to be a very clear justification why any new hop-by-hop option is needed before it is standardized.

Instead of defining new extension headers, it is recommended that the Destination Options header is used to carry optional information that must be examined only by a packet's destination node(s), because they provide better handling and backward compatibility.

If new extension headers are defined, they need to use the following format:

```
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |  Next Header  |  Hdr Ext Len  |                               |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+                               +
 |                                                               |
 .                                                               .
 .                  Header-Specific Data                         .
 .                                                               .
 |                                                               |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Next Header	8-bit selector. Identifies the type of header immediately following the extension header. Uses the same values as the IPv4 Protocol field [IANA-PN].
Hdr Ext Len	8-bit unsigned integer. Length of the Destination Options header in 8-octet units, not including the first 8 octets.
Header Specific Data	Variable-length field. Fields specific to the extension header.

5. Packet Size Issues

IPv6 requires that every link in the Internet have an MTU of 1280 octets or greater. This is known as the IPv6 minimum link MTU. On any link that cannot convey a 1280-octet packet in one piece, link-specific fragmentation and reassembly must be provided at a layer below IPv6.

Links that have a configurable MTU (for example, PPP links [RFC1661]) must be configured to have an MTU of at least 1280 octets; it is recommended that they be configured with an MTU of 1500 octets or greater, to accommodate possible encapsulations (i.e., tunneling) without incurring IPv6-layer fragmentation.

From each link to which a node is directly attached, the node must be able to accept packets as large as that link's MTU.

It is strongly recommended that IPv6 nodes implement Path MTU Discovery [RFC8201], in order to discover and take advantage of path MTUs greater than 1280 octets. However, a minimal IPv6 implementation (e.g., in a boot ROM) may simply restrict itself to sending packets no larger than 1280 octets, and omit implementation of Path MTU Discovery.

In order to send a packet larger than a path's MTU, a node may use the IPv6 Fragment header to fragment the packet at the source and have it reassembled at the destination(s). However, the use of such fragmentation is discouraged in any application that is able to adjust its packets to fit the measured path MTU (i.e., down to 1280 octets).

A node must be able to accept a fragmented packet that, after reassembly, is as large as 1500 octets. A node is permitted to accept fragmented packets that reassemble to more than 1500 octets. An upper-layer protocol or application that depends on IPv6 fragmentation to send packets larger than the MTU of a path should not send packets larger than 1500 octets unless it has assurance that the destination is capable of reassembling packets of that larger size.

6. Flow Labels

The 20-bit Flow Label field in the IPv6 header is used by a source to label sequences of packets to be treated in the network as a single flow.

The current definition of the IPv6 Flow Label can be found in [RFC6437].

7. Traffic Classes

The 8-bit Traffic Class field in the IPv6 header is used by the network for traffic management. The value of the Traffic Class bits in a received packet or fragment might be different from the value sent by the packet's source.

The current use of the Traffic Class field for Differentiated Services and Explicit Congestion Notification is specified in [RFC2474] and [RFC3168].

8. Upper-Layer Protocol Issues

8.1. Upper-Layer Checksums

Any transport or other upper-layer protocol that includes the addresses from the IP header in its checksum computation must be modified for use over IPv6, to include the 128-bit IPv6 addresses instead of 32-bit IPv4 addresses. In particular, the following illustration shows the TCP and UDP "pseudo-header" for IPv6:

```
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                                                               |
   +                                                               +
   |                                                               |
   +                         Source Address                        +
   |                                                               |
   +                                                               +
   |                                                               |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                                                               |
   +                                                               +
   |                                                               |
   +                      Destination Address                      +
   |                                                               |
   +                                                               +
   |                                                               |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                   Upper-Layer Packet Length                   |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                      zero                     |  Next Header  |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

- o If the IPv6 packet contains a Routing header, the Destination Address used in the pseudo-header is that of the final destination. At the originating node, that address will be in the last element of the Routing header; at the recipient(s), that address will be in the Destination Address field of the IPv6 header.

- o The Next Header value in the pseudo-header identifies the upper-layer protocol (e.g., 6 for TCP or 17 for UDP). It will differ from the Next Header value in the IPv6 header if there are extension headers between the IPv6 header and the upper-layer header.

- The Upper-Layer Packet Length in the pseudo-header is the length of the upper-layer header and data (e.g., TCP header plus TCP data). Some upper-layer protocols carry their own length information (e.g., the Length field in the UDP header); for such protocols, that is the length used in the pseudo-header. Other protocols (such as TCP) do not carry their own length information, in which case the length used in the pseudo-header is the Payload Length from the IPv6 header, minus the length of any extension headers present between the IPv6 header and the upper-layer header.

- Unlike IPv4, the default behavior when UDP packets are originated by an IPv6 node is that the UDP checksum is not optional. That is, whenever originating a UDP packet, an IPv6 node must compute a UDP checksum over the packet and the pseudo-header, and, if that computation yields a result of zero, it must be changed to hex FFFF for placement in the UDP header. IPv6 receivers must discard UDP packets containing a zero checksum and should log the error.

- As an exception to the default behavior, protocols that use UDP as a tunnel encapsulation may enable zero-checksum mode for a specific port (or set of ports) for sending and/or receiving. Any node implementing zero-checksum mode must follow the requirements specified in "Applicability Statement for the Use of IPv6 UDP Datagrams with Zero Checksums" [RFC6936].

The IPv6 version of ICMP [RFC4443] includes the above pseudo-header in its checksum computation; this is a change from the IPv4 version of ICMP, which does not include a pseudo-header in its checksum. The reason for the change is to protect ICMP from misdelivery or corruption of those fields of the IPv6 header on which it depends, which, unlike IPv4, are not covered by an internet-layer checksum. The Next Header field in the pseudo-header for ICMP contains the value 58, which identifies the IPv6 version of ICMP.

8.2. Maximum Packet Lifetime

Unlike IPv4, IPv6 nodes are not required to enforce maximum packet lifetime. That is the reason the IPv4 "Time-to-Live" field was renamed "Hop Limit" in IPv6. In practice, very few, if any, IPv4 implementations conform to the requirement that they limit packet lifetime, so this is not a change in practice. Any upper-layer protocol that relies on the internet layer (whether IPv4 or IPv6) to limit packet lifetime ought to be upgraded to provide its own mechanisms for detecting and discarding obsolete packets.

8.3. Maximum Upper-Layer Payload Size

When computing the maximum payload size available for upper-layer data, an upper-layer protocol must take into account the larger size of the IPv6 header relative to the IPv4 header. For example, in IPv4, TCP's Maximum Segment Size (MSS) option is computed as the maximum packet size (a default value or a value learned through Path MTU Discovery) minus 40 octets (20 octets for the minimum-length IPv4 header and 20 octets for the minimum-length TCP header). When using TCP over IPv6, the MSS must be computed as the maximum packet size minus 60 octets, because the minimum-length IPv6 header (i.e., an IPv6 header with no extension headers) is 20 octets longer than a minimum-length IPv4 header.

8.4. Responding to Packets Carrying Routing Headers

When an upper-layer protocol sends one or more packets in response to a received packet that included a Routing header, the response packet(s) must not include a Routing header that was automatically derived by "reversing" the received Routing header UNLESS the integrity and authenticity of the received Source Address and Routing header have been verified (e.g., via the use of an Authentication header in the received packet). In other words, only the following kinds of packets are permitted in response to a received packet bearing a Routing header:

- o Response packets that do not carry Routing headers.
- o Response packets that carry Routing headers that were NOT derived by reversing the Routing header of the received packet (for example, a Routing header supplied by local configuration).
- o Response packets that carry Routing headers that were derived by reversing the Routing header of the received packet IF AND ONLY IF the integrity and authenticity of the Source Address and Routing header from the received packet have been verified by the responder.

9. IANA Considerations

RFC 2460 is referenced in a number of IANA registries. These include:

- o Internet Protocol Version 6 (IPv6) Parameters [IANA-6P]
- o Assigned Internet Protocol Numbers [IANA-PN]

- o ONC RPC Network Identifiers (netids) [IANA-NI]
- o Network Layer Protocol Identifiers (NLPIDs) of Interest [IANA-NL]
- o Protocol Registries [IANA-PR]

The IANA has updated these references to point to this document.

10. Security Considerations

IPv6, from the viewpoint of the basic format and transmission of packets, has security properties that are similar to IPv4. These security issues include:

- o Eavesdropping, where on-path elements can observe the whole packet (including both contents and metadata) of each IPv6 datagram.
- o Replay, where the attacker records a sequence of packets off of the wire and plays them back to the party that originally received them.
- o Packet insertion, where the attacker forges a packet with some chosen set of properties and injects it into the network.
- o Packet deletion, where the attacker removes a packet from the wire.
- o Packet modification, where the attacker removes a packet from the wire, modifies it, and reinjects it into the network.
- o Man-in-the-middle (MITM) attacks, where the attacker subverts the communication stream in order to pose as the sender to receiver and the receiver to the sender.
- o Denial-of-service (DoS) attacks, where the attacker sends large amounts of legitimate traffic to a destination to overwhelm it.

IPv6 packets can be protected from eavesdropping, replay, packet insertion, packet modification, and MITM attacks by use of the "Security Architecture for the Internet Protocol" [RFC4301]. In addition, upper-layer protocols such as Transport Layer Security (TLS) or Secure Shell (SSH) can be used to protect the application-layer traffic running on top of IPv6.

There is not any mechanism to protect against DoS attacks. Defending against these type of attacks is outside the scope of this specification.

IPv6 addresses are significantly larger than IPv4 addresses making it much harder to scan the address space across the Internet and even on a single network link (e.g., Local Area Network). See [RFC7707] for more information.

IPv6 addresses of nodes are expected to be more visible on the Internet as compared with IPv4 since the use of address translation technology is reduced. This creates some additional privacy issues such as making it easier to distinguish endpoints. See [RFC7721] for more information.

The design of IPv6 extension header architecture, while adding a lot of flexibility, also creates new security challenges. As noted below, issues relating to the Fragment extension header have been resolved, but it's clear that for any new extension header designed in the future, the security implications need to be examined thoroughly, and this needs to include how the new extension header works with existing extension headers. See [RFC7045] for more information.

This version of the IPv6 specification resolves a number of security issues that were found with the previous version [RFC2460] of the IPv6 specification. These include:

- o Revised the text to handle the case of fragments that are whole datagrams (i.e., both the Fragment Offset field and the M flag are zero). If received, they should be processed as a reassembled packet. Any other fragments that match should be processed independently. The Fragment creation process was modified to not create whole datagram fragments (Fragment Offset field and the M flag are zero). See [RFC6946] and [RFC8021] for more information.

- o Removed the paragraph in Section 5 that required including a Fragment header to outgoing packets if an ICMP Packet Too Big message reporting a Next-Hop MTU is less than 1280. See [RFC6946] for more information.

- o Changed the text to require that IPv6 nodes must not create overlapping fragments. Also, when reassembling an IPv6 datagram, if one or more of its constituent fragments is determined to be an overlapping fragment, the entire datagram (and any constituent fragments) must be silently discarded. Includes clarification that no ICMP error message should be sent if overlapping fragments are received. See [RFC5722] for more information.

- o Revised the text to require that all headers through the first upper-layer header are in the first fragment. See [RFC7112] for more information.

- Incorporated the updates from [RFC5095] and [RFC5871] to remove the description of the Routing Header type 0 (RH0), that the allocations guidelines for Routing headers are specified in RFC 5871, and removed RH0 from the list of required extension headers.

Security issues relating to other parts of IPv6 including addressing, ICMPv6, Path MTU Discovery, etc., are discussed in the appropriate specifications.

11. References

11.1. Normative References

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Appendix A. Formatting Guidelines for Options

This appendix gives some advice on how to lay out the fields when designing new options to be used in the Hop-by-Hop Options header or the Destination Options header, as described in Section 4.2. These guidelines are based on the following assumptions:

- One desirable feature is that any multi-octet fields within the Option Data area of an option be aligned on their natural boundaries, i.e., fields of width n octets should be placed at an integer multiple of n octets from the start of the Hop-by-Hop or Destination Options header, for n = 1, 2, 4, or 8.

- Another desirable feature is that the Hop-by-Hop or Destination Options header take up as little space as possible, subject to the requirement that the header be an integer multiple of 8 octets long.

- It may be assumed that, when either of the option-bearing headers are present, they carry a very small number of options, usually only one.

These assumptions suggest the following approach to laying out the fields of an option: order the fields from smallest to largest, with no interior padding, then derive the alignment requirement for the entire option based on the alignment requirement of the largest field (up to a maximum alignment of 8 octets). This approach is illustrated in the following examples:

Example 1

If an option X required two data fields, one of length 8 octets and one of length 4 octets, it would be laid out as follows:

```
                                +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
                                | Option Type=X |Opt Data Len=12|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                         4-octet field                         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+                         8-octet field                         +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Its alignment requirement is 8n+2, to ensure that the 8-octet field starts at a multiple-of-8 offset from the start of the enclosing header. A complete Hop-by-Hop or Destination Options header containing this one option would look as follows:

```
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Next Header  | Hdr Ext Len=1 | Option Type=X |Opt Data Len=12|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                         4-octet field                         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+                         8-octet field                         +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Example 2

If an option Y required three data fields, one of length 4 octets, one of length 2 octets, and one of length 1 octet, it would be laid out as follows:

```
                                                +-+-+-+-+-+-+-+-+
                                                | Option Type=Y |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|Opt Data Len=7 | 1-octet field |         2-octet field         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                         4-octet field                         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Its alignment requirement is 4n+3, to ensure that the 4-octet field starts at a multiple-of-4 offset from the start of the enclosing header. A complete Hop-by-Hop or Destination Options header containing this one option would look as follows:

```
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Next Header  | Hdr Ext Len=1 | Pad1 Option=0 | Option Type=Y |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|Opt Data Len=7 | 1-octet field |         2-octet field         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                         4-octet field                         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| PadN Option=1 |Opt Data Len=2 |       0       |       0       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Example 3

A Hop-by-Hop or Destination Options header containing both options X and Y from Examples 1 and 2 would have one of the two following formats, depending on which option appeared first:

```
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Next Header  | Hdr Ext Len=3 | Option Type=X |Opt Data Len=12|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                         4-octet field                         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+                         8-octet field                         +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| PadN Option=1 |Opt Data Len=1 |       0       | Option Type=Y |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|Opt Data Len=7 | 1-octet field |         2-octet field         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                         4-octet field                         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| PadN Option=1 |Opt Data Len=2 |       0       |       0       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+

+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Next Header  | Hdr Ext Len=3 | Pad1 Option=0 | Option Type=Y |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|Opt Data Len=7 | 1-octet field |         2-octet field         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                         4-octet field                         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| PadN Option=1 |Opt Data Len=4 |       0       |       0       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|       0       |       0       | Option Type=X |Opt Data Len=12|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                         4-octet field                         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+                         8-octet field                         +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Appendix B. Changes Since RFC 2460

This memo has the following changes from RFC 2460.

- Removed IP Next Generation from the Abstract.

- Added text in Section 1 that the data transmission order is the same as IPv4 as defined in RFC 791.

- Clarified the text in Section 3 about decrementing the Hop Limit.

- Clarified that extension headers (except for the Hop-by-Hop Options header) are not processed, inserted, or deleted by any node along a packet's delivery path.

- Changed requirement for the Hop-by-Hop Options header to a "may", and added a note to indicate what is expected regarding the Hop-by-Hop Options header.

- Added a paragraph to Section 4 to clarify how extension headers are numbered and which are upper-layer headers.

- Added a reference to the end of Section 4 to the "IPv6 Extension Header Types" IANA registry.

- Incorporated the updates from RFCs 5095 and 5871 to remove the description of RH0, that the allocations guidelines for routing headers are specified in RFC 5871, and removed RH0 from the list of required extension headers.

- Revised Section 4.5 on IPv6 fragmentation based on updates from RFCs 5722, 6946, 7112, and 8021. This includes:

  - Revised the text to handle the case of fragments that are whole datagrams (i.e., both the Fragment Offset field and the M flag are zero). If received, they should be processed as a reassembled packet. Any other fragments that match should be processed independently. The revised Fragment creation process was modified to not create whole datagram fragments (Fragment Offset field and the M flag are zero).

  - Changed the text to require that IPv6 nodes must not create overlapping fragments. Also, when reassembling an IPv6 datagram, if one or more its constituent fragments is determined to be an overlapping fragment, the entire datagram (and any constituent fragments) must be silently discarded. Includes a clarification that no ICMP error message should be sent if overlapping fragments are received.

  - Revised the text to require that all headers through the first Upper-Layer header are in the first fragment. This changed the text describing how packets are fragmented and reassembled and added a new error case.

  - Added text to the Fragment header process on handling exact duplicate fragments.

  - Updated the Fragmentation header text to correct the inclusion of an Authentication Header (AH) and noted No Next Header case.

  - Changed terminology in the Fragment header section from "Unfragmentable Headers" to "Per-Fragment headers".

  - Removed the paragraph in Section 5 that required including a Fragment header to outgoing packets if an ICMP Packet Too Big message reports a Next-Hop MTU less than 1280.

  - Changed the text to clarify MTU restriction and 8-byte restrictions, and noted the restriction on headers in the first fragment.

- In Section 4.5, added clarification noting that some fields in the IPv6 header may also vary across the fragments being reassembled, and that other specifications may provide additional instructions for how they should be reassembled. See, for example, Section 5.3 of [RFC3168].

- Incorporated the update from RFC 6564 to add a new Section 4.8 that describes recommendations for defining new extension headers and options.

- Added text to Section 5 to define "IPv6 minimum link MTU".

- Simplified the text in Section 6 about Flow Labels and removed what was Appendix A ("Semantics and Usage of the Flow Label Field"); instead, pointed to the current specifications of the IPv6 Flow Label field in [RFC6437] and the Traffic Class field in [RFC2474] and [RFC3168].

- Incorporated the update made by RFC 6935 ("IPv6 and UDP Checksums for Tunneled Packets") in Section 8. Added an exception to the default behavior for the handling of UDP packets with zero checksums for tunnels.

- Added instruction to Section 9, "IANA Considerations", to change references to RFC 2460 to this document.

- Revised and expanded Section 10, "Security Considerations".

- Added a paragraph to the Acknowledgments section acknowledging the authors of the updating documents.

- Updated references to current versions and assigned references to normative and informative.

- Made changes to resolve the errata on RFC 2460. These are:

  Erratum ID 2541 [Err2541]: This erratum notes that RFC 2460 didn't update RFC 2205 when the length of the flow label was changed from 24 to 20 bits from RFC 1883. This issue was resolved in RFC 6437 where the flow label is defined. This specification now references RFC 6437. No change is required.

  Erratum ID 4279 [Err4279]: This erratum noted that the specification doesn't handle the case of a forwarding node receiving a packet with a zero Hop Limit. This is fixed in Section 3 of this specification.

  Erratum ID 4657 [Err4657]: This erratum proposed text that extension headers must never be inserted by any node other than the source of the packet. This was resolved in Section 4, "IPv6 Extension Headers".

  Erratum ID 4662 [Err4662]: This erratum proposed text that extension headers, with one exception, are not examined, processed, modified, inserted, or deleted by any node along a packet's delivery path. This was resolved in Section 4, "IPv6 Extension Headers".

  Erratum ID 2843: This erratum is marked "Rejected". No change was made.

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