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Operational Implications of IPv6 Packets with Extension Headers
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Abstract

This document summarizes the operational implications of IPv6 extension headers specified in the IPv6 protocol specification ([RFC8200](#)), and attempts to analyze reasons why packets with IPv6 extension headers are often dropped in the public Internet.

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[1.](#) Introduction

IPv6 Extension Headers (EHs) allow for the extension of the IPv6 protocol, and provide support for core functionality such as IPv6 fragmentation. However, common implementation limitations suggest that EHs present a challenge for IPv6 packet routing equipment and middle-boxes, and evidence exists that IPv6 packets with EHs are intentionally dropped in the public Internet in some network deployments.

The authors of this document have been involved in numerous discussions about IPv6 extension headers (both within the IETF and in other fora), and have noticed that the security and operational implications associated with IPv6 EHs were unknown to the larger audience participating in these discussions.

This document has the following goals:

- o Raise awareness about the operational and security implications of IPv6 Extension Headers specified in [\[RFC8200\]](#), and present reasons why some networks resort to intentionally dropping packets containing IPv6 Extension Headers.
- o Highlight areas where current IPv6 support by networking devices maybe sub-optimal, such that the aforementioned support is improved.
- o Highlight operational issues associated with IPv6 extension headers, such that those issues are considered in IETF standardization efforts.

[Section 3](#) provides background information about the IPv6 packet structure and associated implications. [Section 4](#) of this document summarizes the previous work that has been carried out in the area of IPv6 extension headers. [Section 5](#) discusses packet forwarding engine constraints in contemporary routers. [Section 6](#) discusses why contemporary routers and middle-boxes may need to access Layer-4 information to make a forwarding decision. Finally, [Section 7](#) discusses the operational implications of IPv6 EHs.

[2.](#) Disclaimer

This document analyzes the operational challenges represented by packets that employ IPv6 Extension Headers, and documents some of the operational reasons why these packets are often dropped in the public Internet. This document is not a recommendation to drop such packets, but rather an analysis of why they are dropped.

[3.](#) Background Information

It is useful to compare the basic structure of IPv6 packets against that of IPv4 packets, and analyze the implications of the two different packet structures.

IPv4 packets have a variable-length header size, that allows for the use of IPv4 "options" -- optional information that may be of use by nodes processing IPv4 packets. The IPv4 header length is specified in the IHL header field of the mandatory IPv4 header, and must be in

the range from 20 octets (the minimum IPv4 header size) to 60 octets (accommodating at most 40 octets of options). The upper-layer protocol type is specified via the "Protocol" field of the mandatory IPv4 header.

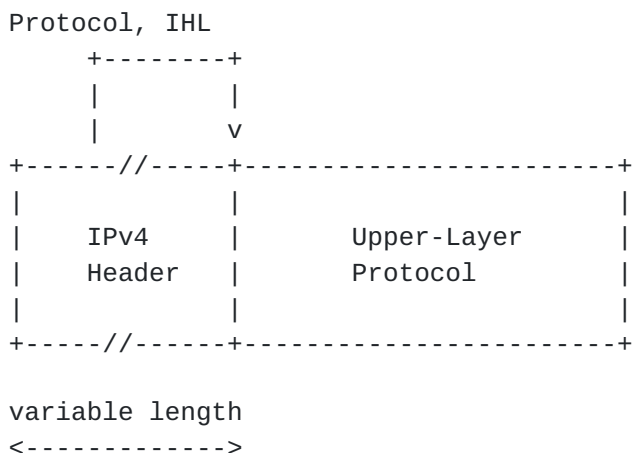


Figure 1: IPv4 Packet Structure

IPv6 took a different approach to the IPv6 packet structure. Rather than employing a variable-length header as IPv4 does, IPv6 employs a linked-list-like packet structure, where a mandatory fixed-length IPv6 header is followed by an arbitrary number of optional extension headers, with the upper-layer header being the last header in the IPv6 header chain. Each extension header typically specifies its length (unless it is implicit from the extension header type), and the "next header" type that follows in the IPv6 header chain.

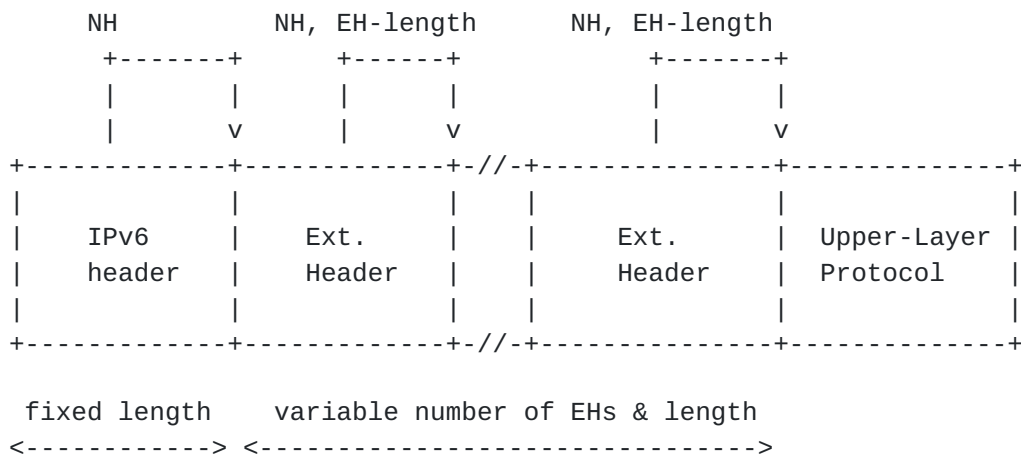


Figure 2: IPv6 Packet Structure

This packet structure has the following implications:

- o [\[RFC8200\]](#) requires the entire IPv6 header chain to be contained in the first fragment of a packet, therefore limiting the IPv6 extension header chain to the size of the Path-MTU.
- o Other than the Path-MTU constraints, there are no other limits to the number of IPv6 EHs that may be present in a packet. Therefore, there is no upper-limit regarding "how deep into the IPv6 packet" the upper-layer may be found.
- o The only way for a node to obtain the upper-layer protocol type or find the upper-layer protocol header is to parse and process the entire IPv6 header chain, in sequence, starting from the mandatory IPv6 header, until the last header in the IPv6 header chain is found.

4. Previous Work on IPv6 Extension Headers

Some of the operational implications of IPv6 Extension Headers have been discussed in IETF circles:

- o [\[I-D.taylor-v6ops-fragdrop\]](#) discusses a rationale for which operators drop IPv6 fragments.
- o [\[I-D.wkumari-long-headers\]](#) discusses possible issues arising from "long" IPv6 header chains.
- o [\[I-D.kampanakis-6man-ipv6-eh-parsing\]](#) describes how inconsistencies in the way IPv6 packets with extension headers are parsed by different implementations could result in evasion of security controls, and presents guidelines for parsing IPv6 extension headers with the goal of providing a common and consistent parsing methodology for IPv6 implementations.
- o [\[I-D.ietf-opsec-ipv6-eh-filtering\]](#) analyzes the security implications of IPv6 EHs, and the operational implications of dropping packets that employ IPv6 EHs and associated options.
- o [\[RFC7113\]](#) discusses how some popular RA-Guard implementations are subject to evasion by means of IPv6 extension headers.
- o [\[RFC8900\]](#) analyzes the fragility introduced by IP fragmentation.

A number of recent RFCs have discussed issues related to IPv6 extension headers, specifying updates to a previous revision of the IPv6 standard ([\[RFC2460\]](#)), many of which have now been incorporated into the current IPv6 core standard ([\[RFC8200\]](#)) or the IPv6 Node Requirements ([\[RFC8504\]](#)). Namely,

- o [\[RFC5095\]](#) discusses the security implications of Routing Header Type 0 (RTH0), and deprecates it.
- o [\[RFC5722\]](#) analyzes the security implications of overlapping fragments, and provides recommendations in this area.
- o [\[RFC7045\]](#) clarifies how intermediate nodes should deal with IPv6 extension headers.
- o [\[RFC7112\]](#) discusses the issues arising in a specific fragmentation case where the IPv6 header chain is fragmented into two or more fragments (and formally forbids such fragmentation case).
- o [\[RFC6946\]](#) discusses a flawed (but common) processing of the so-called IPv6 "atomic fragments", and specified improved processing of such packets.
- o [\[RFC8021\]](#) deprecates the generation of IPv6 atomic fragments.
- o [\[RFC8504\]](#) clarifies processing rules for packets with extension headers, and also allows hosts to enforce limits on the number of options included in IPv6 EHs.
- o [\[RFC7739\]](#) discusses the security implications of predictable fragment Identification values, and provides recommendations for the generation of these values.
- o [\[RFC6980\]](#) analyzes the security implications of employing IPv6 fragmentation with Neighbor Discovery for IPv6, and formally recommends against such usage.

Additionally, [\[RFC8200\]](#) has relaxed the requirement that "all nodes examine and process the Hop-by-Hop Options header" from [\[RFC2460\]](#), by specifying that only nodes that have been explicitly configured to process the Hop-by-Hop Options header are required to do so.

A number of studies have measured the extent to which packets employing IPv6 extension headers are dropped in the public Internet:

- o [\[PMTUD-Blackholes\]](#) and [\[Linkova-Gont-IEPG90\]](#) presented some preliminary measurements regarding the extent to which packet containing IPv6 EHs are dropped in the public Internet.
- o [\[RFC7872\]](#) presents more comprehensive results and documents the methodology for obtaining the presented results.
- o [\[Huston-2017\]](#) and [\[Huston-2020\]](#) measured packet drops resulting from IPv6 fragmentation when communicating with DNS servers.

5. Packet Forwarding Engine Constraints

Most contemporary routers use dedicated hardware (e.g. ASICs or NPUs) to determine how to forward packets across their internal fabrics (see [[IEPG94-Scudder](#)] and [[APNIC-Scudder](#)] for details). One of the common methods of handling next-hop lookup is to send a small portion of the ingress packet to a lookup engine with specialised hardware (e.g. ternary CAM or RLDRAM) to determine the packet's next-hop. Technical constraints mean that there is a trade-off between the amount of data sent to the lookup engine and the overall performance of the lookup engine. If more data is sent, the lookup engine can inspect further into the packet, but the overall performance of the system will be reduced. If less data is sent, the overall performance of the router will be increased but the packet lookup engine may not be able to inspect far enough into a packet to determine how it should be handled.

NOTE:

For example, contemporary high-end routers can use up to 192 bytes of header (Cisco ASR9000 Typhoon) or 384 bytes of header (Juniper MX Trio).

If a hardware forwarding engine on a contemporary router cannot make a forwarding decision about a packet because critical information is not sent to the look-up engine, then the router will normally drop the packet.

NOTE:

[Section 6](#) discusses some of the reasons for which a contemporary router might need to access layer-4 information to make a forwarding decision.

Historically, some packet forwarding engines punted packets of this form to the control plane for more in-depth analysis, but this is unfeasible on most current router architectures as a result of the vast difference between the hardware forwarding capacity of the router and processing capacity of the control plane and the size of the management link which connects the control plane to the forwarding plane.

If an IPv6 header chain is sufficiently long that it exceeds the packet look-up capacity of the router, the router could resort to dropping the packet, as a result of being unable to determine how the packet should be handled.

5.1. Recirculation

Although TLV chains are amenable to iterative processing on architectures that have packet look-up engines with deep inspection capabilities, some packet forwarding engines manage IPv6 Extension Header chains using recirculation. This approach processes Extension Headers one at a time: when processing on one Extension Header is completed, the packet is looped back through the processing engine again. This recirculation process continues repeatedly until there are no more Extension Headers left to be processed.

Recirculation is typically used on packet forwarding engines with limited look-up capability, because it allows arbitrarily long header chains to be processed without the complexity and cost associated with packet forwarding engines which have deep look-up capabilities. However, recirculation can impact the forwarding capacity of hardware, as each packet will pass through the processing engine multiple times. Depending on configuration, the type of packets being processed, and the hardware capabilities of the packet forwarding engine, this could impact data-plane throughput performance on the router.

6. Requirement to Process Layer-3/layer-4 information in Intermediate Systems

The following subsections discuss some of the reasons for which contemporary routers and middle-boxes may need to process Layer-3/layer-4 information to make a forwarding decision.

6.1. ECMP and Hash-based Load-Sharing

In the case of ECMP (equal cost multi path) load sharing, the router on the sending side of the link needs to make a decision regarding which of the links to use for a given packet. Since round-robin usage of the links is usually avoided to prevent packet reordering, forwarding engines need to use a mechanism that will consistently forward the same data streams down the same forwarding paths. Most forwarding engines achieve this by calculating a simple hash using an n-tuple gleaned from a combination of layer-2 through to layer-4 packet header information. This n-tuple will typically use the src/dst MAC address, src/dst IP address, and if possible further layer-4 src/dst port information. Layer-4 port information can increase the entropy of the hash, and it is often thought desirable to use it if available.

We note that in the IPv6 world, flows are expected to be identified by means of the IPv6 Flow Label [[RFC6437](#)]. Thus, ECMP and Hash-based Load-Sharing would be possible without the need to process the entire

IPv6 header chain to obtain upper-layer information to identify flows. However, we note that for a long time many IPv6 implementations failed to set the Flow Label, and ECMP and Hash-based Load-Sharing devices also did not employ the Flow Label for performing their task.

Clearly, widespread support of [\[RFC6437\]](#) would relieve middle-boxes from having to process the entire IPv6 header chain, making Flow Label-based ECMP and Hash-based Load-Sharing [\[RFC6438\]](#) feasible.

While support of [\[RFC6437\]](#) is currently widespread for current versions of all popular host implementations, there is still only marginal usage of the IPv6 Flow Label for ECMP and load balancing [\[Cunha-2020\]](#). A contributing factor could be the issues that have been found in host implementations and middle-boxes [\[Jaeggli-2018\]](#).

[6.2.](#) Enforcing infrastructure ACLs

Generally speaking, infrastructure ACLs (iACLs) drop unwanted packets destined to parts of a provider's infrastructure, because they are not operationally needed and can be used for attacks of different sorts against router control planes. Some traffic needs to be differentiated depending on layer-3 or layer-4 criteria to achieve a useful balance of protection and functionality, for example:

- o Permit some amount of ICMP echo (ping) traffic towards a router's addresses for troubleshooting.
- o Permit BGP sessions on the shared network of an exchange point (potentially differentiating between the amount of packets/seconds permitted for established sessions and connection establishment), but do not permit other traffic from the same peer IP addresses.

[6.3.](#) DDoS Management and Customer Requests for Filtering

The case of customer DDoS protection and edge-to-core customer protection filters is similar in nature to the infrastructure ACL protection. Similar to infrastructure ACL protection, layer-4 ACLs generally need to be applied as close to the edge of the network as possible, even though the intent is usually to protect the customer edge rather than the provider core. Application of layer-4 DDoS protection to a network edge is often automated using Flowspec [\[RFC5575\]](#).

For example, a web site that normally only handled traffic on TCP ports 80 and 443 could be subject to a volumetric DDoS attack using NTP and DNS packets with randomised source IP address, thereby rendering traditional [\[RFC5635\]](#) source-based real-time black hole

mechanisms useless. In this situation, DDoS protection ACLs could be configured to block all UDP traffic at the network edge without impairing the web server functionality in any way. Thus, being able to block arbitrary protocols at the network edge can avoid DDoS-related problems both in the provider network and on the customer edge link.

6.4. Network Intrusion Detection and Prevention

Network Intrusion Detection Systems (NIDS) examine network traffic and try to identify traffic patterns that can be correlated to network-based attacks. These systems generally inspect application-layer traffic (if possible), but at the bare minimum inspect layer-4 flows. When attack activity is inferred, the operator is signaled of the potential intrusion attempt.

Network Intrusion Prevention Systems (IPS) operate similarly to NIDS's, but they can also prevent intrusions by reacting to detected attack attempts by e.g., triggering packet filtering policies at firewalls and other devices.

Use of extension headers can result problematic for NIDS/IPS, since:

- o Extension headers increase the complexity of resulting traffic, and the associated work and system requirements to process it.
- o Use of unknown extension headers can prevent an NIDS/IPS to process layer-4 information
- o Use of IPv6 fragmentation requires a stateful fragment-reassembly operation, even for decoy traffic employing forged source addresses (see e.g. [[nmap](#)]).

As a result, in order to increase the efficiency or effectiveness of these systems, packets employing IPv6 extension headers are often dropped at the network ingress point(s) of networks that deploy these systems.

6.5. Firewalling

Firewalls enforce security policies by means of packet filtering. These systems generally inspect layer-3 and layer-4 traffic, and can often also examine application-layer traffic flows.

As with NIDS/IPS ([Section 6.4](#)), use of IPv6 extension headers can represent a challenge to network firewalls, since:

- o Extension headers increase the complexity of resulting traffic, and the associated work and system requirements to process it (see e.g. [[Zack-FW-Benchmark](#)]).
- o Use of unknown extension headers can prevent firewalls to process layer-4 information
- o Use of IPv6 fragmentation requires a stateful fragment-reassembly operation, even for decoy traffic employing forged source addresses (see e.g. [[nmap](#)]).

Additionally, a common firewall filtering policy is the so-called "default deny", where all traffic is blocked (by default), and only expected traffic is added to an "allow/accept list".

As a result, whether because of the challenges represented by extension headers or because the use of IPv6 extension headers has not been explicitly allowed, packets employing IPv6 extension headers are often dropped by network firewalls.

[7.](#) Operational Implications

[7.1.](#) Inability to Find Layer-4 Information

As discussed in [Section 6](#), contemporary routers and middle-boxes that need to find the layer-4 header must process the entire IPv6 extension header chain. When such devices are unable to obtain the required information, the forwarding device has the option to drop the packet unconditionally, forward the packet unconditionally, or process the packet outside the normal forwarding path. Forwarding packets unconditionally will usually allow for the circumvention of security controls (see e.g. [Section 6.5](#)), while processing packets outside of the normal forwarding path will usually open the door to DoS attacks (see e.g. [Section 5](#)). Thus, in these scenarios, devices often simply resort to dropping such packets unconditionally.

[7.2.](#) Route-Processor Protection

Most contemporary routers have a fast hardware-assisted forwarding plane and a loosely coupled control plane, connected together with a link that has much less capacity than the forwarding plane could handle. Traffic differentiation cannot be done by the control plane side, because this would overload the internal link connecting the forwarding plane to the control plane.

The Hop-by-Hop Options header has been particularly challenging since in most circumstances, the corresponding packet is punted to the control plane for processing. As a result, operators usually drop

IPv6 packets containing this extension header. Please see [[RFC6192](#)] for advice regarding protection of the router control plane.

7.3. Inability to Perform Fine-grained Filtering

Some router implementations do not have support for fine-grained filtering of IPv6 extension headers. For example, an operator that wishes to drop packets containing Routing Header Type 0 (RHT0), may only be able to filter on the extension header type (Routing Header). This could result in an operator enforcing a more coarse filtering policy (e.g. "drop all packets containing a Routing Header" vs. "only drop packets that contain a Routing Header Type 0").

7.4. Security Concerns Associated with IPv6 Extension Headers

The security implications of IPv6 Extension Headers generally fall into one or more of these categories:

- o Evasion of security controls
- o DoS due to processing requirements
- o DoS due to implementation errors
- o Extension Header-specific issues

Unlike IPv4 packets where the upper-layer protocol can be trivially found by means of the "IHL" ("Internet Header Length") IPv4 header field, the structure of IPv6 packets is more flexible and complex, and can represent a challenge for devices that need to find this information, since locating upper-layer protocol information requires that all IPv6 extension headers be examined. This has presented implementation difficulties, and some packet filtering mechanisms that require upper-layer information (even if just the upper layer protocol type) can be trivially circumvented by inserting IPv6 Extension Headers between the main IPv6 header and the upper layer protocol. [[RFC7113](#)] describes this issue for the RA-Guard case, but the same techniques could be employed to circumvent other IPv6 firewall and packet filtering mechanisms. Additionally, implementation inconsistencies in packet forwarding engines can result in evasion of security controls [[I-D.kampanakis-6man-ipv6-eh-parsing](#)] [[Atlasis2014](#)] [[BH-EU-2014](#)].

Packets with attached IPv6 Extension Headers can impact performance on routers that forward them. Unless appropriate mitigations are put in place (e.g., packet dropping and/or rate-limiting), an attacker could simply send a large amount of IPv6 traffic employing IPv6

Extension Headers with the purpose of performing a Denial of Service (DoS) attack (see [Section 7](#) for further details).

NOTE:

In the most trivial case, a packet that includes a Hop-by-Hop Options header might go through the slow forwarding path, and be processed by the router's CPU. Another possible case might be where a router that has been configured to enforce an ACL based on upper-layer information (e.g., upper layer protocol or TCP Destination Port), needs to process the entire IPv6 header chain (in order to find the required information), causing the packet to be processed in the slow path [[Cisco-EH-Cons](#)]. We note that, for obvious reasons, the aforementioned performance issues can affect other devices such as firewalls, Network Intrusion Detection Systems (NIDS), etc. [[Zack-FW-Benchmark](#)]. The extent to which these devices are affected is typically implementation-dependent.

IPv6 implementations, like all other software, tend to mature with time and wide-scale deployment. While the IPv6 protocol itself has existed for over 20 years, serious bugs related to IPv6 Extension Header processing continue to be discovered (see e.g. [[Cisco-Frag1](#)], [[Cisco-Frag2](#)], and [[FreeBSD-SA](#)]). Because there is currently little operational reliance on IPv6 Extension headers, the corresponding code paths are rarely exercised, and there is the potential for bugs that still remain to be discovered in some implementations.

IPv6 Fragment Headers are employed to allow fragmentation of IPv6 packets. While many of the security implications of the fragmentation / reassembly mechanism are known from the IPv4 world, several related issues have crept into IPv6 implementations. These range from denial of service attacks to information leakage, as discussed in [[RFC7739](#)], [[Bonica-NANOG58](#)] and [[Atlasis2012](#)]).

8. IANA Considerations

There are no IANA registries within this document. The RFC-Editor can remove this section before publication of this document as an RFC.

9. Security Considerations

The security implications of IPv6 extension headers are discussed in [Section 7.4](#). This document does not introduce any new security issues.

10. Acknowledgements

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