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F. Gont
SI6 Networks / UTN-FRH
J. Linkova
Google
T. Chown
University of Southampton
W. Liu
Huawei Technologies

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IPv6 Extension Headers in the Real World
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Abstract

This document summarizes the operational implications of IPv6 extension headers, and presents real-world data regarding the extent to which packets with IPv6 extension headers are filtered in the public Internet, and where in the network such filtering occurs. Additionally, this document provides guidance to operators in troubleshooting IPv6 blackholes resulting from the use of IPv6 extension headers, advice to protocol designers regarding the use of IPv6 extension headers, and a discussion of areas where further work might be needed.

Status of This Memo

This Internet-Draft is submitted in full conformance with the provisions of BCP 78 and BCP 79.

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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, IPv6 Extension Headers have been deemed to present a challenge to IPv6 implementations and networks, and have been assumed/known to be intentionally filtered in some existing IPv6 deployments.

Discussions over the operational implications of IPv6 extension headers and their usability in the public Internet come up over and over again at both in IETF circles and other venues, and not

infrequently some key aspects involving IPv6 extension headers are overlooked.

This document tries raise awareness about the operational implications of IPv6 Extension Headers, and their usability in the public Internet. Additionally, it provides some guidance in troubleshooting IPv6 blackholes resulting from the filtering of packets that employ IPv6 extension headers. Finally, it aims to raise awareness about the operational reality of IPv6 extension headers to protocol designers, and trigger discussion within the IETF community regarding areas where future work might be required.

Section 2 of this document summarizes the work that has been done in the area of IPv6 extension headers. Section 3 discusses the operational implications of IPv6 Extension Headers. Section 4 presents real-world data regarding the extent to which IPv6 Extension Headers are usable in the public Internet. Section 5 provides advise to protocol designers regarding the use of IPv6 extension headers, and aims to raise awareness about the possible interoperability implications on existing protocols. Finally, Section 6 provides some guidance in troubleshooting of problems that may arise as a result of filtering packets that employ IPv6 Extension Headers.

2. Previous Work on IPv6 Extension Headers

Some of the implications of IPv6 Extension Headers have been discussed in IETF circles. For example, [I-D.taylor-v6ops-fragdrop] discusses a rationale for which operators filter IPv6 fragments. [I-D.wkumari-long-headers] discusses possible issues arising from "long" IPv6 header chains. [RFC7045] clarifies how intermediate nodes should deal with IPv6 extension headers. [RFC7112] discusses the issues arising in a specific case where the IPv6 header chain is fragmented into two or more fragments (and formally forbids such case). [I-D.kampanakis-6man-ipv6-eh-parsing] describes how inconsistencies in the way IPv6 packets with extension headers are parsed by different implementations may result in evasion of security

controls, and presents guidelines for parsing IPv6 extension headers with a goal of providing a common and consistent parsing methodology for IPv6 implementations. [RFC6980] analyzes the security implications of employing IPv6 fragmentation with Neighbor Discovery for IPv6, and formally recommends against such usage. Finally, [RFC7123] discusses how some popular RA-Guard implementations are subject to evasion by means of IPv6 extension headers.

While packets employing IPv6 Extension Headers have been "known" to be dropped in some IPv6 deployments, there was not much concrete data on the topic. Some preliminary measurements have been presented in [PMTUD-Blackholes], [Gont-IEPG88] and [Gont-Chown-IEPG89], whereas

[Linkova-Gont-IEPG90] presents more comprehensive results on which Section 4 of this document is based.

3. Operational Implications

3.1. Performance Issues

Many IPv6 router implementations suffer from a negative performance impact when IPv6 Extension Headers are employed.

In the most trivial case, a packet that includes a Hop-by-Hop Options header will typically go through the slow forwarding path, and be processed by the router's CPU. Another case is that in which a router that has been configured to enforce an ACL based on upper-layer information (e.g., upper layer protocol or TCP Destination Port). In such case, the router will need to process the entire IPv6 header chain in order to find the required information, and this may cause the packet to be processed in the slow path [Cisco-EH-Cons].

Processing a large amounts of traffic in the slow path may cause the router to be unable to handle the same traffic loads when compared to normal packets, and may result in Denial of Service (DoS) scenarios.

We note that, for obvious reasons, the aforementioned performance issues may also affect other devices such as firewalls, Network Intrusion Detection Systems (NIDS), etc. [Zack-FW-Benchmark].

3.2. Security Implications

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

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

Different from IPv4, where the upper-layer protocol can be found after the variable-length IPv4 header, the structure of IPv6 packets is both more flexible and complex. Namely, finding the upper-layer information may imply processing the (daisy-chain like) entire IPv6 header chain. This has been often overlooked, and a number of security devices have been found to be trivially evasible by inserting one or more 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 can be employed for circumventing e.g. some IPv6 firewalls. Additionally, inconsistencies in how some packets may be processed may result in evasion of security controls [I-D.kampanakis-6man-ipv6-eh-parsing] [Atlasis2014].

As noted in Section 3.1, packets that employ IPv6 Extension Headers may have a negative performance impact on the handling devices. Unless appropriate mitigations are put in place (e.g., packet filtering 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.

IPv6 implementations, as virtually every piece of software, tend to mature over time. While the IPv6 protocol itself (and many implementations) have been around for a long time already, bugs in IPv6 Extension Header processing have been recently found in a number of implementations. Because there is currently almost no reliance on IPv6 Extension headers, the corresponding code paths are rarely exercised, and there is the potential that bugs still remain to be discovered in some implementations.

Besides the general implications of IPv6 Extension Headers, each Extension Header tends to its own specific implications. One particular case is that of the Fragment Header, which is employed to provide the fragmentation function in IPv6. While many of the security implications of the fragmentation/reassembly mechanism are known from the IPv4 world, many of the related issues have creeped into IPv6 implementations. They range from Denial of Service attacks to information leakage (see e.g. [I-D.ietf-6man-predictable-fragment-id], [Bonica-NANOG58], [Atlasis2012]).

4. Support of IPv6 Extension Headers in the Public Internet

This section summarizes the results obtained when measuring the support of IPv6 Extension Headers on the path towards different types of public IPv6 servers. Two sources were employed for the list of public IPv6 servers: the "World IPv6 Launch Day" site (http://www.worldipv6launch.org/) and Alexa's top 1M web sites (http://www.alexa.com). For each list of domain names, the following datasets were obtained:

- Web servers (AAAA records of the aforementioned list)
- Mail servers (MX -> AAAA of such list)
- Name servers (NS -> AAAA of such list)

Duplicate and unreachable addresses were eliminated from each of those lists prior to obtaining the results below. Additionally, addresses that were found to be unreachable were discarded from the dataset (please see Appendix A for further details).

For each of the aforementioned address sets, three different types of probes were performed:

- IPv6 packets with a Destination Options header of 8 bytes
- IPv6 packets resulting in two IPv6 fragments of 512 bytes each (approximately)
- IPv6 packets with a Hop-by-Hop Options header of 8 bytes

In the case of packets with Destination Options Header and Hop-by-Hop Options header, the desired EH size was achieved by means of PadN options [RFC2460]. The upper-layer protocol of the probe packets was, in all cases, TCP [RFC0793] segments with the Destination Port set to the service port [IANA-PORT-NUMBERS] of the corresponding dataset. For example, the probe packets for all the measurements involving web servers were TCP segments with the destination port set to 80.

Besides obtaining the packet drop rate when employing the aforementioned IPv6 extension headers, we tried to identify whether the Autonomous System (AS) dropping the packets was the same as the Autonomous System of the destination/target address. This is of particular interest since it essentially reveals whether the packet drops are under the control of the intended destination of the packets. Packets dropped by the destination AS are less of a concern, since the device dropping the packets is under the control of the same organization as that to which the packets are destined (hence, it is probably easier to update the filtering policy if deemed necessary). On the other hand, packets dropped by transit ASes are more of a concern, since they affect the deployability and usability of IPv6 extension headers (including IPv6 fragmentation) by a third-party (the destination AS). In any case, we note that it is impossible to tell whether, in those cases where IPv6 packets with extension headers get dropped, the packet drops are the result of an explicit and intended policy, or the result of improper device configuration defaults, buggy devices, etc. Thus, packet drops that occur at the destination AS might still prove to be problematic.

Since there is some ambiguity when identifying the autonomous system to which a specific router belongs, our measurements result in a percentage *range* (see Appendix A.2). In the following tables, the values shown within parentheses represent the estimated range of

possibility that when a packet is dropped, the packet drop occurs in an AS other than the destination AS.

Dataset	DO8	HBH8	FH512
Webservers	11.88% (17.60%-20.80%)	40.70% (31.43%-40.00%)	30.51% (5.08%-6.78%)

Mailservers	17.07% (6.35%-26.98%)	48.86% (40.50%-65.42%)	39.17% (2.91%-12.73%)
Nameservers	15.37% (14.29%-33.46%)	43.25% (42.49%-72.07%)	38.55% (3.90%-13.96%)

Table 1: WIPv6LD dataset: Packet drop rate for different destination types, and estimated percentage of dropped packets that were deemed to be dropped in a different AS (lower, in parentheses)

NOTE: As an example, we note that the cell describing the support of IPv6 packets with DO8 for webservers (containing the value "11.88% (17.60%-20.80%)") should be read as: "When sending IPv6 packets with DO8 to public webservers, 11.88% of such packets get dropped. Among those packets that get dropped, between 17.60%-20.80% of them get dropped at an AS other than the destination AS".

Dataset	DO8	HBH8	FH512
Webservers	10.91% (46.52%-53.23%)	39.03% (36.90%-46.35%)	28.26% (53.64%-61.43%)
Mailservers	11.54% (2.41%-21.08%)	45.45% (41.27%-61.13%)	35.68% (3.15%-10.92%)
Nameservers	21.33% (10.27%-56.80%)	54.12% (50.64%-81.00%)	55.23% (5.66%-32.23%)

Table 2: Alexa's top 1M sites dataset: Packet drop rate for different destination types, and estimated percentage of dropped packets that were deemed to be dropped in a different AS (lower, in parentheses)

There are a number of observations to be made based on the results presented above. Firstly, while it has been generally assumed that it is IPv6 fragments that are dropped by operators, our results

indicate that it is IPv6 extension headers in general that are

dropped. Secondly, our results indicate that a significant percentage of such packet drops occur in transit Autonomous Systems; that is, the packet drops are not under the control of the same organization as the final destination.

5. Implications of Widespread IPv6 Extension Header Filtering

The results presented in Section 4 indicate that at least for part of the public Internet, communication employing IPv6 extension headers is unreliable. The following subsections discuss specific implications arising from this conclusion.

5.1. Advice to Protocol Designers

New protocols that are to operate in the public Internet should consider the effect of widespread filtering of IPv6 extension headers in the public Internet. If IPv6 extension headers are at all employed, a fall-back mechanism that does not rely on IPv6 extension headers should be considered.

5.2. A possible attack vector

The widespread filtering of IPv6 packets employing IPv6 Extension Headers can, in some scenarios, be exploited for malicious purposes: if packets employing IPv6 EHs are known to be filtered on the path from one system (say, "A") to another (say, "B"), an attacker could cause packets sent from A to B to be dropped by sending a forged ICMPv6 Packet Too Big (PTB) [RFC4443] error message to A (with a Next-Hop MTU smaller than 1280), such that subsequent packets from A to B include a fragment header (i.e., they result in atomic fragments [RFC6946]).

Possible scenarios where this attack vector could be exploited include (but are not limited to):

- Communication between any two systems through to public network (e.g., client from/to server or server from/to server), where packets with IPv6 extension headers are filtered by some intermediate router

- Communication between two BGP peers employing IPv6 transport, where these BGP peers implement ACLs to drop IPv6 fragments (to avoid control-plane attacks)

The aforementioned attack vector is exacerbated by the following factors:

- The attacker does not need to forge the IPv6 Source Address of his attack packets. Hence, deployment of simple BCP38 filters will not help as a counter-measure.

- Only the IPv6 addresses of the IPv6 packet embedded in the ICMPv6 payload need to be forged. While one could envision filtering devices enforcing BCP38-style filters on the ICMPv6 payload, the use of extension (by the attacker) could make this difficult, if at all possible.

- Many implementations fail to perform validation checks on the received ICMPv6 error messages, as recommended in Section 5.2 of [RFC4443] and documented in [RFC5927]. It should be noted that in some cases, such as when an ICMPv6 error message has (supposedly) been elicited by a connection-less transport protocol (or some other connection-less protocol being encapsulated in IPv6), it may be virtually impossible to perform validation checks on the received ICMPv6 error messages. And, because of IPv6 extension headers, the ICMPv6 payload might not even contain any useful information on which to perform validation checks.

- Upon receipt of one of the aforementioned ICMPv6 "Packet Too Big" error messages, the Destination Cache [RFC4861] is usually updated to reflect that any subsequent packets to such destination should include a Fragment Header. This means that a single ICMPv6 "Packet Too Big" error message might affect multiple communication instances (e.g., TCP connections) with such destination.

- A node cannot simply "just filter/drop all incoming ICMPv6 Packet Too Big error messages", or else it would create a PMTUD blackhole.

Possible mitigations for this issue include:

- Filtering incoming ICMPv6 Packet Too Big error messages that advertise a Next-Hop MTU smaller than 1280 bytes.

- Artificially reducing the MTU to 1280 bytes and filter incoming ICMPv6 PTB error messages.

Both of these mitigations come at the expense of possibly preventing communication through SIIT [RFC6145] that rely on IPv6 atomic fragments (see [I-D.gont-6man-deprecate-atomfrag-generation]), and also implies that the filtering device has the ability to filter ICMP PTB messages based on the contents of the MTU field.

[I-D.gont-6man-deprecate-atomfrag-generation] has recently proposed to deprecate the generation of IPv6 atomic fragments, and update the

SIIT [RFC6145] such that it does not rely on ICMPv6 atomic fragments. Thus, any of the above mitigations would eliminate the attack vector without any interoperability implications.

5.3. Possible Future Work

The impact of widespread filtering of IPv6 EHs on existing protocols should be considered. In particular, the effect of widespread filtering of IPv6 fragments on the Domain Name System (DNS) [RFC1034] should be evaluated (particularly when it is expected that reliance on IPv6 transport will increase over time).

6. Troubleshooting Packet Drops due to IPv6 Extension Headers

Isolating IPv6 blackholes essentially involves performing IPv6 traceroute for a destination system with and without IPv6 extension headers. The (EH-free) traceroute would provide the full working path towards a destination, while the EH-enabled traceroute would provide the address of the last-responding node for EH-enabled packets (say, "M"). In principle, one could isolate the dropping node by looking-up "M" in the EH-free traceroute, with the dropping node being "M+1" (see Appendix A.1 for caveats).

At the time of this writing, most traceroute implementations do not support IPv6 extension headers. However, the path6 tool [path6] and RIPE Atlas [RIPE-Atlas] provide such support. Additionally, the blackhole6 tool [blackhole6] automates the troubleshooting process and can readily provide information such as: dropping node's IPv6 address, dropping node's Autonomous System, etc.

7. 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.

8. Security Considerations

The security implications of IPv6 extension headers are discussed in

Section 3.2. A specific attack vector that would leverage the widespread filtering of packets with IPv6 EHs (along with possible countermeasures) is discussed in Section 5.2. This document does not introduce any new security issues.

9. Acknowledgements

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Appendix A. Measurements Caveats

A number of issues have needed some consideration when producing the results presented in Section 4. These same issues should be considered when troubleshooting connectivity problems resulting from the use of IPv6 Extension headers.

A.1. Isolating the Dropping Node

Let us assume that we find that IPv6 packets with EHs are being dropped on their way to the destination system 2001:db8:d::1, and that the output of running traceroute towards such destination is:

1. 2001:db8:1:1000::1
2. 2001:db8:2:2000::4
3. 2001:db8:2:4000::1
4. 2001:db8:3:4000::1
5. 2001:db8:3:1000::1
6. 2001:db8:4:4000::1
7. 2001:db8:4:1000::1
8. 2001:db8:5:5000::1
9. 2001:db8:5:6000::1
10. 2001:db8:d::1

Additionally, let us assume that the output of EH-enabled traceroute to the same destination is:

1. 2001:db8:1:1000::1
2. 2001:db8:2:2000::4
3. 2001:db8:2:4000::1
4. 2001:db8:3:4000::1

5. 2001:db8:3:1000::1
6. 2001:db8:4:4000::1

For the sake of brevity, let us refer to the last-responding node in the EH-enabled traceroute ("2001:db8:4:4000::1" in this case) as "M". Assuming both packets in both traceroutes employ the same path, we'll refer to "the node following the last responding node in the EH-enabled traceroute" ("2001:db8:4:1000::1" in our case), as "M+1", etc.

Based on traceroute information above, which node is the one actually dropping the EH-enabled packets will depend on whether the dropping node filters packets on ingress or the egress. If the former, the dropping node will be M+1. If the latter, the dropping node will be "M".

Throughout this document (and our measurements), we assume that nodes perform ingress-filtering. Thus, in our example above the last responding node to the EH-enabled traceroute ("M") is "2001:db8:4:4000::1", and therefore we assume the "node" dropping node to be "2001:db8:4:1000::1" ("M+1").

Additionally, we note that when isolating the dropping node we assume that both the EH-enabled and the EH-free traceroutes result in the same paths. However, this might not be the case.

A.2. Obtaining the Responsible Organization for the Packet Drops

In order to identify the organization operating the dropping node, one would be tempted to lookup the ASN corresponding to the dropping node. However, assuming that M and M+1 are two peering routers, any of these two organizations could be providing the address space employed for such peering. Or, in the case of an Internet eXchange Point (IXP), the address space could correspond to the IXP AS, rather than to any of the participating ASes. Thus, the organization operating the dropping node (M+1) could be the AS for M+1, but it might as well be the AS for M+2. Only when the ASN for M+1 is the same as the ASN for M+2 we have certainty about who the responsible organization for the packet drops is (see slides 21-23 of [Linkova-Gont-IEPG90]).

In the measurement results presented in Section 4, the aforementioned ambiguity results in "percentage ranges" (rather than a specific ratio): the lowest percentage value means that, when in doubt, we

assume the packet drops occur in the same AS as the destination; on the other hand, the highest percentage value means that, when in doubt, we assume the packet drops occur at different AS than the destination AS.

We note that the aforementioned ambiguity should also be considered when troubleshooting and reporting IPv6 packet drops, since identifying the organization responsible for the packet drops might probe to be a non-trivial task.

Finally, we note that a specific organization might be operating more than one Autonomous System. However, our measurements assume that different Autonomous System Numbers imply different organizations.

Authors' Addresses

Fernando Gont
SI6 Networks / UTN-FRH
Evaristo Carriego 2644
Haedo, Provincia de Buenos Aires 1706
Argentina

Phone: +54 11 4650 8472
Email: fgont@si6networks.com
URI: http://www.si6networks.com

J. Linkova
Google
1600 Amphitheatre Parkway
Mountain View, CA 94043
USA

Email: furry@google.com

Tim Chown
University of Southampton
Highfield
Southampton , Hampshire SO17 1BJ
United Kingdom

Email: tjc@ecs.soton.ac.uk

Will(Shucheng) Liu
Huawei Technologies
Bantian, Longgang District
Shenzhen 518129
P.R. China

Email: liushucheng@huawei.com