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# IP Fragmentation Considered Fragile
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Abstract

This document provides an overview of IP fragmentation. It explains how IP fragmentation works and why it is required. As part of that explanation, this document also explains how IP fragmentation reduces the reliability of Internet communication.

This document also proposes alternatives to IP fragmentation. Finally, it provides recommendations for application developers and network operators.

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# 1. Introduction

Operational experience [RFC7872] [Huston] reveals that IP fragmentation reduces the reliability of Internet communication. This document provides an overview of IP fragmentation. It explains how IP fragmentation works and why it is required. As part of that explanation, this document also explains how IP fragmentation reduces the reliability of Internet communication.

This document also proposes alternatives to IP fragmentation. Finally, it provides recommendations for application developers and network operators.

# 2. IP Fragmentation

## 2.1. Links, Paths, MTU and PMTU

An Internet path connects a source node to a destination node. A path can contain links and intermediate systems. If a path contains more than one link, the links are connected in series and an intermediate system connects each link to the next. An intermediate system can be a router or a middle box.

Internet paths are dynamic. Assume that the path from one node to another contains a set of links and intermediate systems. If the network topology changes, that path can also change so that it includes a different set of links and intermediate systems.

Each link is constrained by the number of bytes that it can convey in a single IP packet. This constraint is called the link Maximum Transmission Unit (MTU). IPv4 [RFC0791] requires every link to have an MTU of 68 bytes or greater. IPv6 [RFC8200] requires every link to have an MTU of 1280 bytes or greater. These are called the IPv4 and IPv6 minimum link MTU's.

Each Internet path is constrained by the number of bytes that it can convey in a IP single packet. This constraint is called the Path MTU (PMTU). For any given path, the PMTU is equal to the smallest of its link MTU's. Because Internet paths are dynamic, PMTU is also dynamic.

For reasons described below, source nodes estimate the PMTU between themselves and destination nodes. A source node can produce extremely conservative PMTU estimates in which:

- o The estimate for each IPv4 path is equal to IPv4 minimum link MTU (68 bytes).

- o The estimate for each IPv6 path is equal to the IPv6 minimum link MTU (1280 bytes).

While these conservative estimates are guaranteed to be less than or equal to the actual MTU, they are likely to be much less than the actual PMTU. This may adversely affect upper-layer protocol performance.

By executing Path MTU Discovery (PMTUD) [RFC1191] [RFC8201] procedures, a source node can maintain a less conservative, running estimate of the PMTU between itself and a destination node. According to these procedures, the source node produces an initial PMTU estimate. This initial estimate is equal to the MTU of the first link along path to the destination node. It can be greater than the actual PMTU.

Having produced an initial PMTU estimate, the source node sends non-fragmentable IP packets to the destination node. If one of these packets is larger than the actual PMTU, a downstream router will not be able to forward the packet through the next link along the path. Therefore, the downstream router drops the packet and send an Internet Control Message Protocol (ICMP) [RFC0792] [RFC4443] Packet Too Big (PTB) message to the source node. The ICMP PTB message indicates the MTU of the link through which the packet could not be forwarded. The source node uses this information to refine its PMTU estimate.

PMTUD produces a running estimate of the PMTU between a source node and a destination node. Because PMTU is dynamic, at any given time, the PMTU estimate can differ from the actual PMTU. In order to detect PMTU increases, PMTUD occasionally resets the PMTU estimate to the MTU of the first link along path to the destination node. It then repeats the procedure described above.

Furthermore, PMTUD has the following characteristics:

- o It relies on the network's ability to deliver ICMP PTB messages to the source node.

- o It is susceptible to attack because ICMP messages are easily forged [RFC5927].

FOOTNOTE: According to RFC 0791, every IPv4 host must be capable of receiving a packet whose length is equal to 576 bytes. However, the IPv4 minimum link MTU is not 576. Section 3.2 of RFC 0791 explicitly states that the IPv4 minimum link MTU is 68 bytes.

FOOTNOTE: In the paragraphs above, the term "non-fragmentable packet" is introduced. A non-fragmentable packet can be fragmented at its source. However, it cannot be fragmented by a downstream node. An IPv4 packet whose DF-bit is set to zero is fragmentable. An IPv4 packet whose DF-bit is set to one is non-fragmentable. All IPv6 packets are also non-fragmentable.

FOOTNOTE: In the paragraphs above, the term "ICMP PTB message" is introduced. The ICMP PTB message has two instantiations. In ICMPv4 [RFC0792], the ICMP PTB message is Destination Unreachable message with Code equal to (4) fragmentation needed and DF set. This message was augmented by [RFC1191] to indicates the MTU of the link through which the packet could not be forwarded. In ICMPv6 [RFC4443], the ICMP PTB message is a Packet Too Big Message with Code equal to (0). This message also indicates the MTU of the link through which the packet could not be forwarded.

### 2.2. Upper-layer Protocols

When an upper-layer protocol submits data to the underlying IP module, and the resulting IP packet's length is greater than the PMTU, IP fragmentation may be required. IP fragmentation divides a packet into fragments. Each fragment includes an IP header and a portion of the original packet.

[RFC0791] describes IPv4 fragmentation procedures. IPv4 packets whose DF-bit is set to one cannot be fragmented. IPv4 packets whose DF-bit is set to zero can be fragmented at the source node or by any downstream router. [RFC8200] describes IPv6 fragmentation procedures. IPv6 packets can be fragmented at the source node only.

IPv4 fragmentation differs slightly from IPv6 fragmentation. However, in both IP versions, the upper-layer header appears in the first fragment only. It does not appear in subsequent fragments.

Upper-layer protocols can operate in the following modes:

o  Do not rely on IP fragmentation.

o  Rely on IP source fragmentation only (i.e., fragmentation at the source node).

o  Rely on IP source fragmentation and downstream fragmentation (i.e., fragmentation at any node along the path).

Upper-layer protocols running over IPv4 can operate in the first and third modes (above). Upper-layer protocols running over IPv6 can operate in the first and second modes (above).

Upper-layer protocols that operate in the first two modes (above) require access to the PMTU estimate. In order to fulfil this requirement, they can

- o Estimate the PMTU to be equal to the IPv4 or IPv6 minimum link MTU.
- o Access the estimate that PMTUD produced.
- o Execute PMTUD procedures themselves.
- o Execute Packetization Layer PMTUD (PLPMTUD) [RFC4821] [I-D.fairhurst-tsvwg-datagram-plpmtud] procedures.

According to PLPMTUD procedures, the upper-layer protocol maintains a running PMTU estimate. It does so by sending probe packets of various sizes to its peer and receiving acknowledgements. This strategy differs from PMTUD in that it relies of acknowledgement of received messages, as opposed to ICMP PTB messages concerning dropped messages. Therefore, PLPMTUD does not rely on the network's ability to deliver ICMP PTB messages to the source.

An upper-layer protocol that does not rely on IP fragmentation never causes the underlying IP module to emit

- o A fragmentable IP packet (i.e., an IPv4 packet with the DF-bit set to zero).
- o An IP fragment.
- o A packet whose length is greater than the PMTU estimate.

However, when the PMTU estimate is greater than the actual PMTU, the upper-layer protocol can cause the underlying IP module to emit a packet whose length is greater than the actual PMTU. When this occurs, a downstream router drops the packet and the source node refines its PMTU estimate, employing either PMTUD or PLPMTUD procedures.

When an upper-layer protocol that relies on IP source fragmentation only submits data to the underlying IP module, and the resulting packet is larger than the PMTU estimate, the underlying IP module fragments the packet and emits the fragments. However, the upper-layer protocol never causes the underlying IP module to emit

- o A fragmentable IP packet.
- o A packet whose length is greater than the PMTU estimate.

When the PMTU estimate is greater than the actual PMTU, the upper-layer protocol can cause the underlying IP module to emit a packet whose length is greater than the actual PMTU. When this occurs, a downstream router drops the packet and the source node refines its PMTU estimate, employing either PMTUD or PLPMTUD procedures.

An upper-layer protocol that relies on IP source fragmentation and downstream fragmentation can cause the underlying IP module to emit

o A fragmentable IP packet.

o An IP fragment.

o A packet whose length is greater than the PMTU estimate.

A protocol that relies on IP source fragmentation and downstream fragmentation does not require access to the PMTU estimate. For these protocols, the underlying IP module:

o Fragments all packets whose length exceeds the MTU of the first link along the path to the destination.

o Sets the DF-bit to zero, so that downstream nodes can fragment the packet.

## 3. Requirements Language

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

## 4. IP Fragmentation Reduces Reliability

This section explains how IP fragmentation reduces the reliability of Internet communication.

### 4.1. Middle Box Failures

Many middle boxes require access to the transport-layer header. However, when a packet is divided into fragments, the transport-layer header appears in the first fragment only. It does not appear in subsequent fragments. This omission can prevent middle boxes from delivering their intended services.

For example, assume that a router diverts selected packets from their normal path towards network appliances that support deep packet inspection and lawful intercept. The router selects packets for diversion based upon the following 5-tuple:

- o IP Source Address.
- o IP Destination Address.
- o IPv4 Protocol or IPv6 Next Header.
- o transport-layer source port.
- o transport-layer destination port.

IP fragmentation causes this selection algorithm to behave suboptimally, because the transport-layer header appears only in the first fragment of each packet.

In another example, a middle box remarks a packet's Differentiated Services Code Point [RFC2474] based upon the above mentioned 5-tuple. IP fragmentation causes this process to behave suboptimally, because the transport-layer header appears only in the first fragment of each packet.

In all of the above-mentioned examples, the middle box cannot deliver its intended service without reassembling fragmented packets.

### 4.2. Partial Filtering

IP fragments cause problems for firewalls whose filter rules include decision making based on TCP and UDP ports. As the port information is not in the trailing fragments the firewall may elect to accept all trailing fragments, which may admit certain classes of attack, or may elect to block all trailing fragments, which may block otherwise legitimate traffic, or may elect to reassemble all fragmented packets, which may be inefficient and negatively affect performance.

### 4.3. Suboptimal Load Balancing

Many stateless load-balancers require access to the transport-layer header. Assume that a load-balancer distributes flows among parallel links. In order to optimize load balancing, the load-balancer sends every packet or packet fragment belonging to a flow through the same link.

In order to assign a packet or packet fragment to a link, the load-balancer executes an algorithm. If the packet or packet fragment contains a transport-layer header, the load balancing algorithm accepts the following 5-tuple as input:

- o IP Source Address.

- o IP Destination Address.

- o IPv4 Protocol or IPv6 Next Header.

- o transport-layer source port.

- o transport-layer destination port.

However, if the packet or packet fragment does not contain a transport-layer header, the load balancing algorithm accepts only the following 3-tuple as input:

- o IP Source Address.

- o IP Destination Address.

- o IPv4 Protocol or IPv6 Next Header.

Therefore, non-fragmented packets belonging to a flow can be assigned to one link while fragmented packets belonging to the same flow can be divided between that link and another. This can cause suboptimal load balancing.

### 4.4. Security Vulnerabilities

Security researchers have documented several attacks that rely on IP fragmentation. The following are examples:

- o Overlapping fragment attack [RFC1858]

- o Incomplete data attack (also known as the Rose Attack)

In the overlapping fragment attack, an attacker constructs a series of packet fragments. The first fragment contains an IP header, a transport-layer header, and some transport-layer payload. This fragment complies with local security policy and is allowed to pass through a stateless firewall. A second fragment, having a non-zero offset, overlaps with the first fragment. The second fragment also passes through the stateless firewall. When the packet is reassembled, the transport layer header from the first fragment is overwritten by data from the second fragment. The reassembled packet does not comply with local security policy. Had it traversed the firewall in one piece, the firewall would have rejected it.

A stateless firewall cannot protect against the overlapping fragment attack. However, destination nodes can protect against the overlapping fragment attack by implementing the reassembly procedures described in RFC 1858 and RFC 8200. These reassembly procedures detect the overlap and discard the packet.

The incomplete data attack is a denial of service attack in which the attacker constructs a series of fragmented packets. However, one fragment is missing from each packet so that no packet can be reassembled. This attack causes resource exhaustion on the destination node, possibly denying reassembly services to other flows. The incomplete data attack can be mitigated by limiting reassembly resources dedicated to a particular Source Address or flow.

### 4.5. Blackholing Due to ICMP Loss

As stated above, an upper-layer protocol requires access the PMTU estimate if it:

- o Does not rely on IP fragmentation.
- o Relies on IP source fragmentation only (i.e., fragmentation at the source node).

In order to satisfy this requirement, the upper-layer protocol can:

- o Estimate the PMTU to be equal to the IPv4 or IPv6 minimum link MTU.
- o Access the estimate that PMTUD produced.
- o Execute PMTUD procedures itself.
- o Execute PLPMTUD procedures.

PMTUD relies upon the network's ability to deliver ICMP PTB messages to the source node. Therefore, if an upper-layer protocol relies on PMTUD for its PMTU estimate, it also relies on the networks ability to deliver ICMP PTB messages to the source node.

[RFC4890] states that the PTB messages must not be filtered. However, ICMP delivery is not reliable. It is subject to transient loss and, in some configurations, more persistent delivery issues.

ICMP rate limiting, network congestion and packet corruption can cause transient loss. The effect of rate limiting may be severe, as RFC 4443 recommends strict rate limiting of IPv6 traffic.

While transient loss causes PMTUD to perform less efficiently, it does not cause PMTUD to fail completely. When the conditions contributing to transient loss abate, the network regains its ability to deliver ICMP PTB messages and PMTUD regains its ability to function.

By contrast, more persistent delivery issues cause PMTUD to fail completely. Consider the following example:

A DNS client sends a request to an anycast address. The network routes that DNS request to the nearest instance of that anycast address (i.e., a DNS Server). The DNS server generates a response and sends it back to the DNS client. While the response does not exceed the DNS server's PMTU estimate, it does exceed the actual PMTU.

A downstream router drops the packet and sends an ICMP PTB message the packet's source (i.e., the anycast address). The network routes the ICMP PTB message to the anycast instance closest to the downstream router. Sadly, that anycast instance may not be the DNS server that originated the DNS response. It may be another DNS server with the same anycast address. The DNS server that originated the response may never receive the ICMP PTB message and may never updates it PMTU estimate.

The problem described in this section is specific to PMTUD. It does not occur when the upper-layer protocol obtains its PMTU estimate from PLPMTUD or any other source.

Furthermore, the problem described in this section occurs when the upper-layer protocol does not rely on IP fragmentation, as well as when the upper-layer protocol relies on IP source fragmentation only.

### 4.6. Blackholing Due To Filtering

In RFC 7872, researchers sampled Internet paths to determine whether they would convey packets that contain IPv6 extension headers. Sampled paths terminated at popular Internet sites (e.g., popular web, mail and DNS servers).

The study revealed that at least 28% of the sampled paths did not convey packets containing the IPv6 Fragment extension header. In most cases, fragments were dropped in the destination autonomous system. In other cases, the fragments were dropped in transit autonomous systems.

Another recent study [Huston] confirmed this finding. It reported that 37% of sampled endpoints used IPv6-capable DNS resolvers that were incapable of receiving a fragmented IPv6 response.

It is difficult to determine why network operators drop fragments. In some cases, packet drop may be caused by misconfiguration. In other cases, network operators may consciously choose to drop IPv6 fragments, in order to address the issues raised in Section 4.1 through Section 4.5, above.

## 5. Alternatives to IP Fragmentation

### 5.1. Transport Layer Solutions

The Transport Control Protocol (TCP) [RFC0793]) can be operated in a mode that does not require IP fragmentation.

Applications submit a stream of data to TCP. TCP divides that stream of data into segments, with no segment exceeding the TCP Maximum Segment Size (MSS). Each segment is encapsulated in a TCP header and submitted to the underlying IP module. The underlying IP module prepends an IP header and forwards the resulting packet.

If the TCP MSS is sufficiently small, the underlying IP module never produces a packet whose length is greater than the actual PMTU. Therefore, IP fragmentation is not required.

TCP offers the following mechanisms for MSS management:

- Manual configuration
- PMTUD
- PLPMTUD

For IPv6 nodes, manual configuration is always applicable. If the MSS is manually configured to 1220 bytes and the packet does not contain extension headers, the IP layer will never produce a packet whose length is greater than the IPv6 minimum link MTU (1280 bytes). However, manual configuration prevents TCP from taking advantage of larger link MTU's.

RFC 8200 strongly recommends that IPv6 nodes implement PMTUD, in order to discover and take advantage of path MTUs greater than 1280 bytes. However, as mentioned in Section 2.1, PMTUD relies upon the network's ability to deliver ICMP PTB messages. Therefore, PMTUD is applicable only in environments where the risk of ICMP PTB loss is acceptable.

By contrast, PLPMTUD does not rely upon the network's ability to deliver ICMP PTB messages. However, in many loss-based TCP congestion control algorithms, the dropping of a packet may cause the TCP control algorithm to drop the congestion control window, or even re-start with the entire slow start process. For high capacity, long RTT, large volume TCP streams, the deliberate probing with large packets and the consequent packet drop may impose too harsh a penalty on total TCP throughput for it to be a viable approach. [RFC4821] defines PLPMTUD procedures for TCP.

While TCP will never cause the underlying IP module to emit a packet that is larger than the PMTU estimate, it can cause the underlying IP module to emit a packet that is larger than the actual PMTU. If this occurs, the packet is dropped, the PMTU estimate is updated, the segment is divided into smaller segments and each smaller segment is submitted to the underlying IP module.

The Datagram Congestion Control Protocol (DCCP) [RFC4340] and the Stream Control Protocol (SCP) [RFC4960] also can be operated in a mode that does not require IP fragmentation. They both accept data from an application and divide that data into segments, with no segment exceeding a maximum size. Both DCCP and SCP offer manual configuration, PMTUD and PLPMTUD as mechanisms for managing that maximum size. [I-D.fairhurst-tsvwg-datagram-plpmtud] proposes PLPMTUD procedures for DCCP and SCP.

### 5.2. Application Layer Solutions

[RFC8085] recognizes that IP fragmentation reduces the reliability of Internet communication. Therefore, it offers the following advice regarding applications the run over the User Data Protocol (UDP) [RFC0768].

"An application SHOULD NOT send UDP datagrams that result in IP packets that exceed the Maximum Transmission Unit (MTU) along the path to the destination. Consequently, an application SHOULD either use the path MTU information provided by the IP layer or implement Path MTU Discovery (PMTUD) itself to determine whether the path to a destination will support its desired message size without fragmentation."

RFC 8085 continues:

"Applications that do not follow the recommendation to do PMTU/ PLPMTUD discovery SHOULD still avoid sending UDP datagrams that would result in IP packets that exceed the path MTU. Because the actual path MTU is unknown, such applications SHOULD fall back to sending messages that are shorter than the default effective MTU for sending

(EMTU_S in [RFC1122]). For IPv4, EMTU_S is the smaller of 576 bytes and the first-hop MTU. For IPv6, EMTU_S is 1280 bytes. The effective PMTU for a directly connected destination (with no routers on the path) is the configured interface MTU, which could be less than the maximum link payload size. Transmission of minimum-sized UDP datagrams is inefficient over paths that support a larger PMTU, which is a second reason to implement PMTU discovery."

RFC 8085 assumes that for IPv4, an EMTU_S of 576 is sufficiently small, even though the IPv6 minimum link MTU is 68 bytes.

This advice applies equally to application that run directly over IP.

## 6. Applications That Rely on IPv6 Fragmentation

The following applications rely on IPv6 fragmentation:

- o DNS [RFC1035]

- o OSPFv3 [RFC5340]

- o IP Encapsulations

Each of these applications relies on IPv6 fragmentation to a varying degree. In some cases, that reliance is essential, and cannot be broken without fundamentally changing the protocol. In other cases, that reliance is incidental, and most implementations already take appropriate steps to avoid fragmentation.

This list is not comprehensive, and other protocols that rely on IPv6 fragmentation may exist. They are not specifically considered in the context of this document.

### 6.1. DNS

DNS can obtain transport services from either UDP or TCP. Superior performance and scaling characteristics are observed when DNS runs over UDP.

DNS Servers that execute DNSSEC [RFC4035] procedures are more likely to generate large responses. Therefore, when running over UDP, they are more likely to cause the generation of IPv6 fragments. DNS's reliance upon IPv6 fragmentation is fundamental and cannot be broken without changing the DNS specification.

DNS is an essential part of the Internet architecture. Therefore, this issue is for further study and must be resolved before DNSSEC can be deployed successfully in IPv6 only networks.

### 6.2. OSPFv3

OSPFv3 implementations can emit messages large enough to cause IPv6 fragmentation. However, in keeping with the recommendations of RFC8200, and in order to optimize performance, most OSPFv3 implementations restrict their maximum message size to the IPv6 minimum link MTU.

### 6.3. IP Encapsulations

In this document, IP encapsulations include IP-in-IP [RFC2003], Generic Routing Encapsulation (GRE) [RFC2784], GRE-in-UDP [RFC8086] and Generic Packet Tunneling in IPv6 [RFC2473]. The fragmentation strategy described for GRE in [RFC7588] has been deployed for all of the above-mentioned IP encapsulations. This strategy does not rely on IPv6 fragmentation except in one corner case. (see Section 3.3.2.2 of RFC 7588 and Section 7.1 of RFC 2473). Section 3.3 of [RFC7676] further describes this corner case.

## 7. Recommendation

### 7.1. For Application Developers

Application developers SHOULD NOT develop applications that rely on IPv6 fragmentation.

Application-layer protocols then depend upon IPv6 fragmentation SHOULD be updated to break that dependency.

### 7.2. For Network Operators

As per RFC 4890, network operators MUST NOT filter ICMPv6 PTB messages unless they are known to be forged or otherwise illegitimate. As stated in Section 4.5, filtering ICMPv6 PTB packets causes PMTUD to fail. Many upper-layer protocols rely on PMTUD.

## 8. IANA Considerations

This document makes no request of IANA.

## 9. Security Considerations

This document mitigates some of the security considerations associated with IP fragmentation by discouraging the use of IP fragmentation. It does not introduce any new security vulnerabilities, because it does not introduce any new alternatives to IP fragmentation. Instead, it recommends well-understood alternatives.

## 10. Acknowledgements

TBD

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