IP fragmentation

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Abstract

Internet Protocol (IP) fragmentation plays a vital role in facilitating the transmission of data across diverse network environments. This essay explores the concept of IP fragmentation, shedding light on its purpose and mechanics.

1. Introduction

IP fragmentation serves as the mechanism that allows data packets to traverse networks with varying **Maximum Transmission Unit** (MTU) sizes. Not all networks have the same capacity to transmit data, and it is the role of IP fragmentation to break down large packets into smaller fragments that can successfully traverse networks with lower MTU values. By doing so, IP ensures that data can reach its destination, even when traversing networks with different transmission capabilities.

2. Maximum Size before Fragmentation of ICMP messages

If using an **MTU** of **1500 bytes**, each host can not place more than 1480 byte in the IPv4 payload as data. For the sake of simplicity, we assume to not have any options, and therefore sending only 20-bytes long IPv4 header packets. If the upper layer protocol is **ICMP**, provided that that an ICMP header is 8-bytes long, each host should not include more than **1472 byte** in the ICMP payload. Otherwise, we expect to see fragmentation.

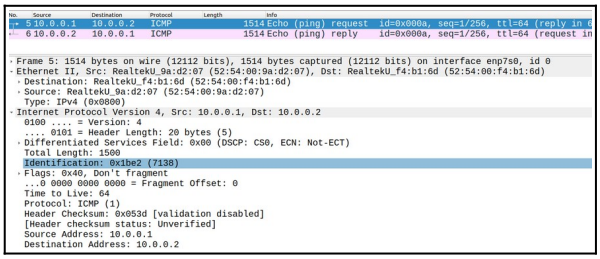
Host H1 has the following configuration:

```
root@h1:~# ip -c a
1: lo: <LOOPBACK,UP,LOWER_UP> mtu 65536 qdisc noqueue state
    link/loopback 00:00:00:00:00:00 brd 00:00:00:00:00:00
    inet 127.0.0.1/8 scope host lo
       valid_lft forever preferred_lft forever
    inet6 ::1/128 scope host
       valid_lft forever preferred_lft forever
2: enp1s0: <BROADCAST,MULTICAST,UP,LOWER_UP> mtu 1500 qdisc
    link/ether 52:54:00:9a:d2:07 brd ff:ff:ff:ff:ff:ff
    inet 10.0.0.1/24 scope global enp1s0
       valid_lft forever preferred_lft forever
```

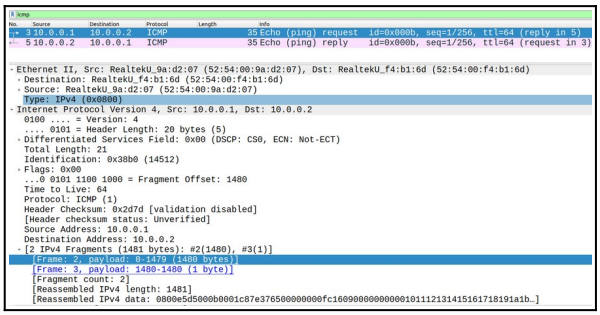
Host H2 has the following configuration:

```
root@h2:~# ip -c a
1: lo: <LOOPBACK,UP,LOWER_UP> mtu 65536 qdisc noqueue state
t qlen 1000
    link/loopback 00:00:00:00:00:00 brd 00:00:00:00:00:00
    inet 127.0.0.1/8 scope host lo
       valid_lft forever preferred_lft forever
    inet6 ::1/128 scope host
       valid_lft forever preferred_lft forever
2: enp7s0: <BROADCAST,MULTICAST,UP,LOWER_UP> mtu 1500 qdisc
oup default qlen 1000
    link/ether 52:54:00:f4:b1:6d brd ff:ff:ff:ff:ff:ff
    inet 10.0.0.2/24 scope global enp7s0
       valid_lft forever preferred_lft forever
```

Sending an ICMP echo-request with 1472 bytes as payload does not cause fragmentation, as followed depicted.



As expected, an ICMP echo-request with 1473 bytes as payload cause fragmentation in the sender because of its own NIC MTU, as followed depicted.

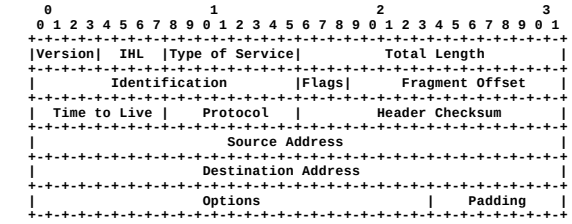


Overall, given an MTU, if sending ICMP messages, fragmentation occurs whenever the ICMP payload size is greater than the:

MTU – len (ICMP header) – len (IP header)

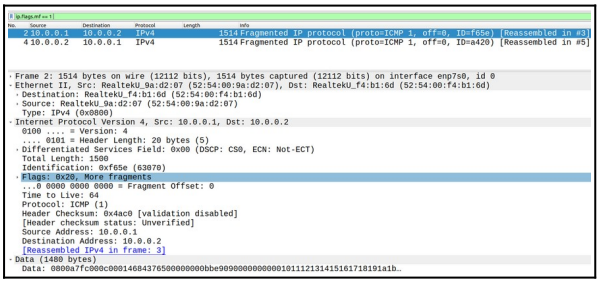
3. IP header fragmentation fields

The IP header contains vital information that guides the process of fragmentation and reassembly. Among its key fields, the **Total Length** (TL) and the **Fragment Offset** (FO) determine the size and positioning of each fragment. Additionally, the **More Fragments** (MF) flag communicates whether a packet has been fragmented or if further fragments are expected.

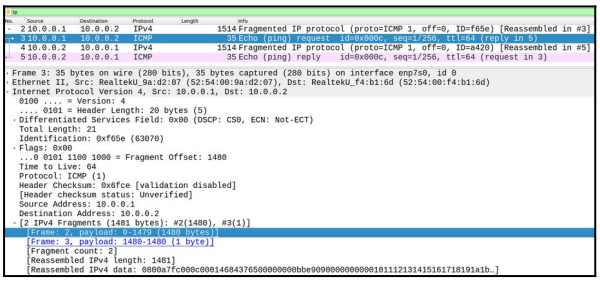


When an IP packet is fragmented, each fragment has the same **Identification**. Conversely, the reassembly process, i.e. the complementary process in the traffic *receiver*, would not able to say which IP packet this fragment belongs to. The More Fragment bit is set to zero, if and if only this is the last fragment, while the rest of fragments have the bit set to one. Finally, the Offset field serves as an index to place the fragment in the proper position in the original packet. In case of the first fragment, this is always equal to zero, while other fragments have something other than zero.

The first ICMP echo-request fragment:



The second ICMP echo-request fragment:



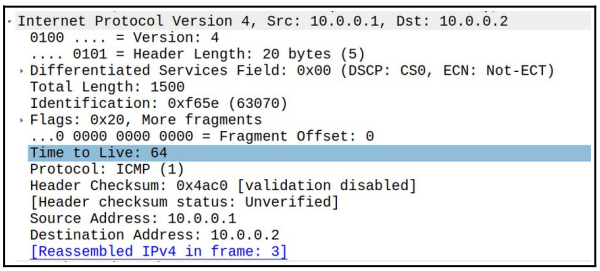
As expected, they share the same Identification, i.e. 0xF65E (63070). The first fragment has More Fragment bit set to one, while Fragment Offset is other than zero. Conversely, the last fragment has Fragment bit set to zero, while the Fragment Offset is other than zero.

3. Reassembly process

The reassembly process occurs in the receiver only. So, if having the two hosts are in a different networks, the router in between will never reassemble the fragments the sender is transferring. At high level, **the overall process relies on a buffer and a timer**; the buffer is used to stage the incoming fragments before sending them all to the upper layer, while the timer is used to avoid the process waiting endlessly for incoming fragments. Since all the fragments share the same Identification, the buffer is also identified by means a key. According to the official RFC, the buffer is key is nothing but the source and destination addresses, the protocol, and the Identification fields computed as follows: `BUFID = src|dst|pto|idf`. As a result, the overall process can be easily translated in pseudo-code:

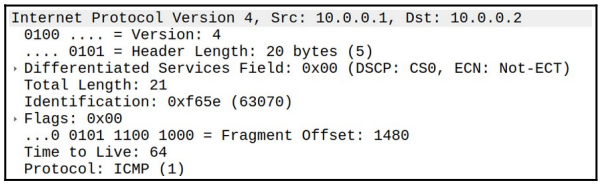
```
// Compute the BUFID
BUFID = src|dst|pto|idf

// Is this a fragment?
IF OFFSET = 0 AND MF = 0: // No, it is not
      // This a packet as whole
      IF BUFID already exists:
            free the buffer with BUFID as key
      send the packet to the upper-layer
      DONE;

ELSE // Yes it is
      IF BUFID not already exists:
            have a new buffer with BUFID as key
      set timer
      // Use FO * 8 as start-point, use
      // and FO + ((TL - (IHL * 4)) + FO * 8
      // to access to the end-point
      copy the fragment payload into the buffer

      // When receiving a fragment, the receiver
      // should track which fragments have been
      // already received
      set the received fragments bit map (RCVFB)
      // If the last fragment
      IF MF = 0:
         compute the overall length
      // If the first fragment
      IF FO = 0:
         copy the IP header in a separated buffer

      IF overall length > 0 AND all bits in the
        RCVFB are set to 1 from 0 to (TDL + 7) / 8:

            free the buffer with BUFID as key
            send the packet to the upper-layer
            DONE;
give up until the next fragment or time is off
```

Notice that the Fragment Offset is a 13 bit-long field, while the overall size of an IP packet is measured in 16 bit. As a result, the real Fragment Offset must always be multiplied by a factor of 8 (Wireshark does it on our behalf). The receiver uses the Fragment Offset as an index to get access the proper location in the buffer; this acts as a C-like pointer in a sort of C-like memcpy() function. As a consequence, until the receiver does not have the last fragment on hand, it can not say how many fragments, or rather how much space is missing in the buffer to be completed. Let's say the receiver receives the first fragment, as follows.



The IP header tells the receiver this is 1500 bytes-long packet, but because of the More Fragment bit this is not the packet as whole. Until the receiver does not have the last fragment, the receiver believes it has just just 1500 out of the theoretical 65546 bytes, i.e. roughly the 2.2%.

Yet, when receiving the last (second) fragment, the receiver can compute how big was the original packet.



If this fragment is 21 bytes-long, therefore the overall size of the original packet was 20 bytes (original IP header size) + 1 byte (last IP fragment payload size) + 1480 bytes (cumulative fragments payload size), i.e. 1501 bytes. If the receiver had received 1500 bytes, it means that it had actually received the 99% of the overall packet size. After receiving the last fragment, the buffer is actually full-filled.

In the end, **if and if only the receiver has the last fragment, it can compute the overall size of the original packet, and therefore exits successfully in case of buffer completed**. However, if the timer goes off, the process exits anyway with an error, that is further translated into ICMP Time Exceeded. In that case, all the fragments are discarded, and the overall packet is considered to be lost.

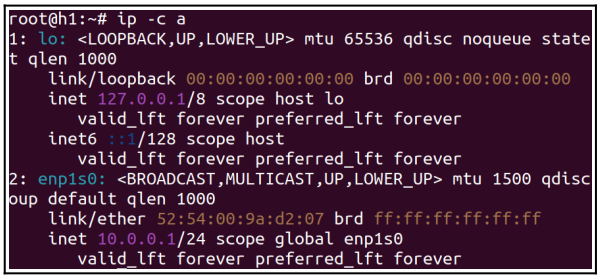
4. IP fragmentation attack

As mentioned before, the receiver allocates a slice of memory to store the incoming fragments. The buffer is free as soon as the receiver gets the last fragment (*More Fragment* set to zero, *Fragment Offset* other than zero and a matching *Identifier* with the stored fragments in the buffer). If the attacker never sends the last fragment, the receiver awaits until the timer expires before evicting the buffer from the memory; **if the attacker is fast enough to force the receivers to allocate more buffer than the receiver removes from memory, then the attacker can carry out a DoS attack**.

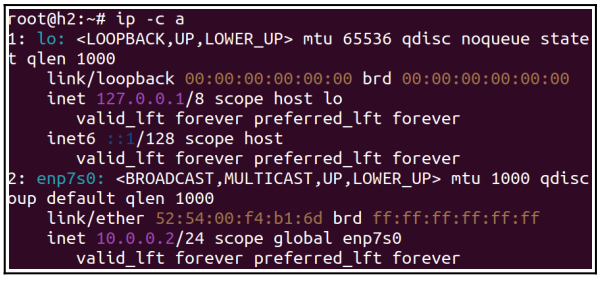
5. Different MTUs on the path

The fragmentation process occurs in the sender only, while the reassembly process is always managed by the final destination.

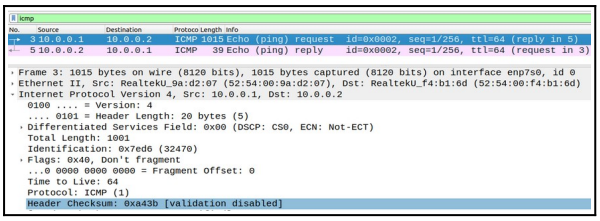
Host H1 has the following configuration, with an MTU of 1500 bytes:



Host H2 has the following configuration, with an MTU of 1000 bytes:



If the host H1 sends an ICMP packet with more than 972 bytes as payload, it tops the H2's MTU. However, since fragmentation only happens at the sender-side, we expect to see the ICMP packet as whole.



As expected, the IP packet which is delivering the ICMP echo-request is not fragmented at all. The overall size is 1001 bytes, which is 1 byte more than the MTU of H2.

If H1 and H2 are in two different networks, there should be a router in between to let them talk each other. As mentioned before, the fragmentation process happens at sender-side only; however, when forwarding a packet to a router, this one acts as a sender. As a result, an IP packet may be fragmented multiple times along the path, since the routers in between connects either two networks using either different technologies, e.g. Ethernet and Token Ring, or two networks with the same technology but with a different set of devices and appliances, e.g. a traditional Ethernet network with an MTU of 1500 bytes and an Ethernet network with jumbo frames, e.g. in a data-center.

Host H1 belongs to the 10.0.0.0/24 network and it has the following configuration, with an MTU of 1500 bytes:

```
root@h1:~# ip -c a
1: lo: <LOOPBACK,UP,LOWER_UP> mtu 65536 qdisc noqueue state UNKNOWN g
    link/loopback 00:00:00:00:00:00 brd 00:00:00:00:00:00
    inet 127.0.0.1/8 scope host lo
       valid_lft forever preferred_lft forever
    inet6 ::1/128 scope host
       valid_lft forever preferred_lft forever
2: enp1s0: <BROADCAST,MULTICAST,UP,LOWER_UP> mtu 1500 qdisc fq_codel
    link/ether 52:54:00:9a:d2:07 brd ff:ff:ff:ff:ff:ff
    inet 10.0.0.1/24 brd 10.0.0.255 scope global noprefixroute enp1s0
       valid_lft forever preferred_lft forever
    inet6 fe80::310d:7add:d3cd:efe9/64 scope link noprefixroute
       valid_lft forever preferred_lft forever
```

```
root@h1:~# route -n
Kernel IP routing table
Destination     Gateway         Genmask         Flags Metric Ref    Use Iface
10.0.0.0        0.0.0.0         255.255.255.0   U     100    0        0 enp1s0
10.0.1.0        10.0.0.254      255.255.255.0   UG    0      0        0 enp1s0
```

Host H2 belongs to the 10.0.1.0/24 network and it has the following configuration, with an MTU of 1500 bytes:

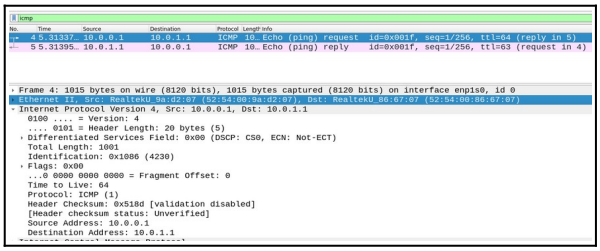
```
root@h2:~# ip -c a
1: lo: <LOOPBACK,UP,LOWER_UP> mtu 65536 qdisc noqueue state UNKNOWN group defa
    link/loopback 00:00:00:00:00:00 brd 00:00:00:00:00:00
    inet 127.0.0.1/8 scope host lo
       valid_lft forever preferred_lft forever
    inet6 ::1/128 scope host
       valid_lft forever preferred_lft forever
2: enp7s0: <BROADCAST,MULTICAST,UP,LOWER_UP> mtu 1500 qdisc fq_codel state UP
    link/ether 52:54:00:f4:b1:6d brd ff:ff:ff:ff:ff:ff
    inet 10.0.1.1/24 brd 10.0.1.255 scope global noprefixroute enp7s0
       valid_lft forever preferred_lft forever
    inet6 fe80::56d5:b717:faf2:f16b/64 scope link noprefixroute
       valid_lft forever preferred_lft forever
    inet6 fe80::5054:ff:fef4:b16d/64 scope link
       valid_lft forever preferred_lft forever
```

```
root@h2:~# route -n
Kernel IP routing table
Destination     Gateway         Genmask         Flags Metric Ref    Use Iface
10.0.0.0        10.0.1.254      255.255.255.0   UG    0      0        0 enp7s0
10.0.1.0        0.0.0.0         255.255.255.0   U     100    0        0 enp7s0
```

H3 is a dual-homed host, and it plays as a router, with an MTU of 1500 bytes for the network 10.0.0.0/24 and an MTU of 1000 bytes for the network 10.0.1.0/24:

```
root@h3:~# ip -c a
1: lo: <LOOPBACK,UP,LOWER_UP> mtu 65536 qdisc noqueue state UNKNOWN group def
    link/loopback 00:00:00:00:00:00 brd 00:00:00:00:00:00
    inet 127.0.0.1/8 scope host lo
       valid_lft forever preferred_lft forever
    inet6 ::1/128 scope host
       valid_lft forever preferred_lft forever
2: enp1s0: <BROADCAST,MULTICAST,UP,LOWER_UP> mtu 1500 qdisc fq_codel state UP
    link/ether 52:54:00:86:67:07 brd ff:ff:ff:ff:ff:ff
    inet 10.0.0.254/24 brd 10.0.0.255 scope global noprefixroute enp1s0
       valid_lft forever preferred_lft forever
3: enp7s0: <BROADCAST,MULTICAST,UP,LOWER_UP> mtu 1000 qdisc fq_codel state UP
    link/ether 52:54:00:b5:9c:3e brd ff:ff:ff:ff:ff:ff
    inet 10.0.1.254/24 brd 10.0.1.255 scope global noprefixroute enp7s0
       valid_lft forever preferred_lft forever
```

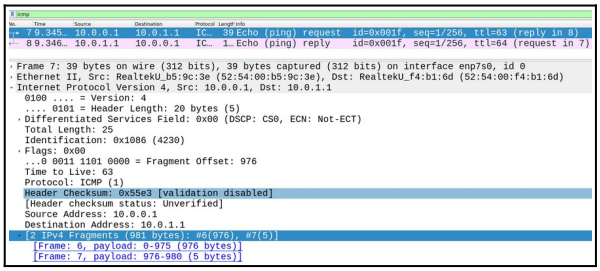
The router (H3) receives an IP packet of 1001 bytes from the interface *enp1s0* (52:54:00:86:67:07).



According to the routing table, the packet is supposed to exit the router from the interface *enp7s0*; however, since the MTU is 1000 bytes on that link, the router has to break up the packet.

```
root@h3:~# ip route
10.0.0.0/24 dev enp1s0 proto kernel scope link src 10.0.0.254 metric 102
10.0.1.0/24 dev enp7s0 proto kernel scope link src 10.0.1.254 metric 103
```

As expected, the out-coming packet is fragmented because of the router output interface MTU.



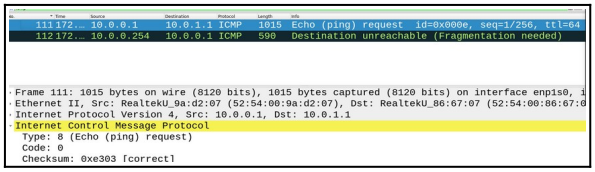
6. Path MTU discovery

IP fragmentation can cause performance and latency issues when fragments are affected by packet loss. As mentioned before, even if the receiver does non have a fragment on hand, it must discard all the other ones,

causing a severe loss. As a result, if the sender could know in advance which network interface, i.e. to be traversed, has the lowest MTU, this could generate smaller, minimum MTU-compliant packets between itself and its recipient. The RFC 1191 defines ***Path MTU discovery***, a simple process through which a host can detect a path MTU smaller than its interface MTU. Two components are key to this process: a) the *Don't Fragment (DF)* bit of the IP header; b) the inner code of the ICMP *Destination Unreachable* message, *Fragmentation Needed*. Setting the DF bit in an IP packet avoids a router from performing fragmentation when it encounters an MTU less than the packet size. Instead, the packet is discarded and an ICMP Fragmentation Needed message is sent to the originating host. Essentially, the router is indicating that it needs to fragment the packet but the DF flag won't allow for it.

```
-M pmtudisc_opt
    Select Path MTU Discovery strategy.  pmtudisc_option may be either
    do (prohibit fragmentation, even local one), want (do PMTU
    discovery, fragment locally when packet size is large), or dont (do
    not set DF flag).
```

As expected, if telling *ping* command to have **-M do**, the sender will set the DF bit to one: this packet can not be fragmented by anyone, including the sender itself. As a result, the router returns an ICMP Error message, i.e. Destination Unreachable, Fragmentation Needed.



This router not only communicates that H2 is not reachable but also the MTU which, in fact, denied the delivery of the traffic. In this way, H1 learns the maximally accepted MTU to send traffic to H2.

```
▸ Internet Protocol Version 4, Src: 10.0.0.254, Dst: 10.0.0.1
▾ Internet Control Message Protocol
    Type: 3 (Destination unreachable)
    Code: 4 (Fragmentation needed)
    Checksum: 0xe010 [correct]
    [Checksum Status: Good]
    Unused: 0000
    MTU of next hop: 1000
  ▸ Internet Protocol Version 4, Src: 10.0.0.1, Dst: 10.0.1.1
```

The maximum MTU accepted along the path is therefore cached by H1.

```
root@h1:~# sudo ip route get 10.0.1.1
10.0.1.1 via 10.0.0.254 dev enp1s0 src 10.0.0.1 uid 0
    cache expires 16sec mtu 1000
```

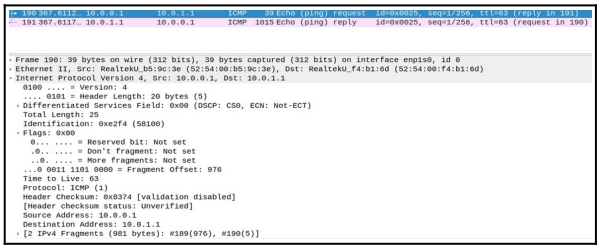
As long as that information is stored in memory, if a running applications generates traffic for H2 which however exceeds the MTU reported by the router, H1 will automatically proceed to fragmentation; conversely, if fragmentation is forbidden explicitly, H1 will not send traffic at all.

As expected, if H1 sends a too much large ICMP message which can not be fragmented (*-M do*), then the router tells H1 there is an MTU of 1000 bytes on the output interface, and therefore the packet can not be delivered successfully. If H1 sends again the same packet, no packet exit the NIC because of a local error, i.e. an over-sized packet which can not be fragmented.

```
root@h1:~# ping 10.0.1.1 -c 1 -s 973 -M do
PING 10.0.1.1 (10.0.1.1) 973(1001) bytes of data.
From 10.0.0.254 icmp_seq=1 Frag needed and DF set (mtu = 1000)

--- 10.0.1.1 ping statistics ---
1 packets transmitted, 0 received, +1 errors, 100% packet loss, time 0ms

root@h1:~# ping 10.0.1.1 -c 1 -s 973 -M do
PING 10.0.1.1 (10.0.1.1) 973(1001) bytes of data.
ping: local error: message too long, mtu=1000

--- 10.0.1.1 ping statistics ---
1 packets transmitted, 0 received, +1 errors, 100% packet loss, time 0ms
```

As expected, on the other hand, if the option is *-M dont*, H1 enables fragmentation and because of the previous router hint, H1 manages the fragmentation. In this case, the packet is successfully sent.

```
root@h1:~# ping 10.0.1.1 -c 1 -s 973 -M dont
PING 10.0.1.1 (10.0.1.1) 973(1001) bytes of data.
981 bytes from 10.0.1.1: icmp_seq=1 ttl=63 time=1.24 ms

--- 10.0.1.1 ping statistics ---
1 packets transmitted, 1 received, 0% packet loss, time 0ms
rtt min/avg/max/mdev = 1.241/1.241/1.241/0.000 ms
root@h1:~#
```



7. References

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Linux Documentation,
https://docs.kernel.org/networking/ip-sysctl.html