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IPv6 Performance and Diagnostic Metrics (PDM) Destination Option

Abstract

To assess performance problems, this document describes optional headers embedded in each packet that provide sequence numbers and timing information as a basis for measurements. Such measurements may be interpreted in real time or after the fact. This document specifies the Performance and Diagnostic Metrics (PDM) Destination Options header. The field limits, calculations, and usage in measurement of PDM are included in this document.

Status of This Memo

This is an Internet Standards Track document.

This document is a product of the Internet Engineering Task Force (IETF). It represents the consensus of the IETF community. It has received public review and has been approved for publication by the Internet Engineering Steering Group (IESG). Further information on Internet Standards is available in Section 2 of RFC 7841.

Information about the current status of this document, any errata, and how to provide feedback on it may be obtained at https://www.rfc-editor.org/info/rfc8250.

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1. Background

To assess performance problems, measurements based on optional sequence numbers and timing may be embedded in each packet. Such measurements may be interpreted in real time or after the fact.

As defined in RFC 8200 [RFC8200], destination options are carried by the IPv6 Destination Options extension header. Destination options include optional information that need be examined only by the IPv6 node given as the destination address in the IPv6 header, not by routers or other "middleboxes". This document specifies the

Performance and Diagnostic Metrics (PDM) destination option. The field limits, calculations, and usage in measurement of the PDM Destination Options header are included in this document.

1.1. Terminology

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.

1.2. Rationale for Defined Solution

The current IPv6 specification does not provide timing, nor does it provide a similar field in the IPv6 main header or in any extension header. The IPv6 PDM destination option provides such fields.

Advantages include:

1. Real measure of actual transactions.

2. Ability to span organizational boundaries with consistent instrumentation.

3. No time synchronization needed between session partners.

4. Ability to handle all transport protocols (TCP, UDP, the Stream Control Transmission Protocol (SCTP), etc.) in a uniform way.

PDM provides the ability to determine quickly if the (latency) problem is in the network or in the server (application). That is, it is a fast way to do triage. For more information on the background and usage of PDM, see Appendix A.

1.3. IPv6 Transition Technologies

In the path to full implementation of IPv6, transition technologies such as translation or tunneling may be employed. It is possible that an IPv6 packet containing PDM may be dropped if using IPv6 transition technologies. For example, an implementation using a

translation technique (IPv6 to IPv4) that does not support or recognize the IPv6 Destination Options extension header may simply drop the packet rather than translating it without the extension header.

It is also possible that some devices in the network may not correctly handle multiple IPv6 extension headers, including the IPv6 Destination Option. For example, adding the PDM header to a packet may push the Layer 4 information to a point in the packet where it is not visible to filtering logic, and the packet may be dropped. This kind of situation is expected to become rare over time.

2. Measurement Information Derived from PDM

Each packet contains information about the sender and receiver. In IP, the identifying information is called a "5-tuple".

The 5-tuple consists of:

```
SADDR: IP address of the sender
SPORT: Port for the sender
DADDR: IP address of the destination
DPORT: Port for the destination
PROTC: Upper-layer protocol (TCP, UDP, ICMP, etc.)
```

PDM contains the following base fields (scale fields intentionally left out):

```
PSNTP   : Packet Sequence Number This Packet
PSNLR   : Packet Sequence Number Last Received
DELTATLR: Delta Time Last Received
DELTATLS: Delta Time Last Sent
```

Other fields for storing time scaling factors are also in PDM and

will be described in Section 3.

This information, combined with the 5-tuple, allows the measurement of the following metrics:

1. Round-trip delay

2. Server delay

2.1. Round-Trip Delay

Round-trip *network* delay is the delay for packet transfer from a source host to a destination host and then back to the source host. This measurement has been defined, and its advantages and disadvantages are discussed in "A Round-trip Delay Metric for IPPM" [RFC2681].

2.2. Server Delay

Server delay is the interval between when a packet is received by a device and the first corresponding packet is sent back in response. This may be "server processing time". It may also be a delay caused by acknowledgments. Server processing time includes the time taken by the combination of the stack and application to return the response. The stack delay may be related to network performance. If this aggregate time is seen as a problem and there is a need to make

a clear distinction between application processing time and stack delay, including that caused by the network, then more client-based measurements are needed.

3. Performance and Diagnostic Metrics Destination Option Layout

3.1. Destination Options Header

The IPv6 Destination Options extension header [RFC8200] is used to carry optional information that needs to be examined only by a packet's destination node(s). The Destination Options header is identified by a Next Header value of 60 in the immediately preceding header and is defined in RFC 8200 [RFC8200]. The IPv6 Performance and Diagnostic Metrics (PDM) destination option is implemented as an IPv6 Option carried in the Destination Options header. PDM does not

require time synchronization.

3.2. Performance and Diagnostic Metrics Destination Option

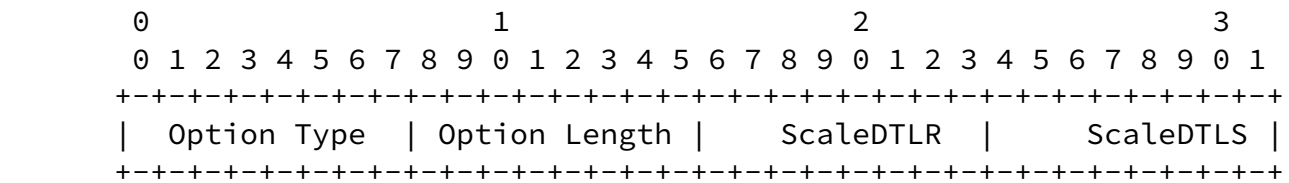
3.2.1. PDM Layout

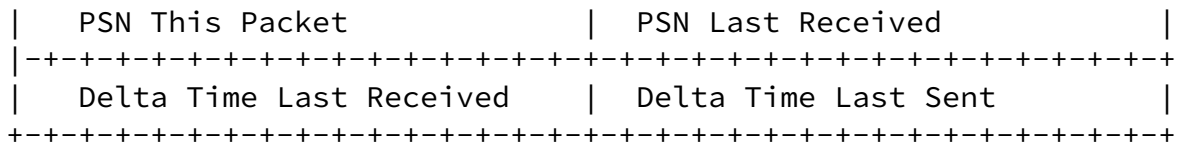
The IPv6 PDM destination option contains the following fields:

```
SCALEDTLR: Scale for Delta Time Last Received
SCALEDTLS: Scale for Delta Time Last Sent
PSNTP    : Packet Sequence Number This Packet
PSNLR    : Packet Sequence Number Last Received
DELTATLR : Delta Time Last Received
DELTATLS : Delta Time Last Sent
```

PDM has alignment requirements. Following the convention in IPv6, these options are aligned in a packet so that multi-octet values within the Option Data field of each option fall on natural boundaries (i.e., fields of width n octets are placed at an integer multiple of n octets from the start of the header, for n = 1, 2, 4, or 8) [RFC8200].

The PDM destination option is encoded in type-length-value (TLV) format as follows:





Option Type

0x0F

In keeping with RFC 8200 [RFC8200], the two high-order bits of the Option Type field are encoded to indicate specific processing of the option; for the PDM destination option, these two bits MUST be set to 00.

The third high-order bit of the Option Type field specifies whether or not the Option Data of that option can change en route to the packet's final destination.

In PDM, the value of the third high-order bit MUST be 0.

Option Length

8-bit unsigned integer. Length of the option, in octets, excluding the Option Type and Option Length fields. This field MUST be set to 10.

Scale Delta Time Last Received (SCALEDTLR)

8-bit unsigned integer. This is the scaling value for the Delta Time Last Received (DELTATLR) field. The possible values are from 0 to 255. See Appendix B for further discussion on timing considerations and formatting of the scaling values.

Scale Delta Time Last Sent (SCALEDTLS)

8-bit signed integer. This is the scaling value for the Delta Time Last Sent (DELTATLS) field. The possible values are from 0 to 255.

Packet Sequence Number This Packet (PSNTP)

16-bit unsigned integer. This field will wrap. It is intended for use while analyzing packet traces.

This field is initialized at a random number and incremented monotonically for each packet of the session flow of the 5-tuple. The random-number initialization is intended to make it harder to spoof and insert such packets.

Operating systems MUST implement a separate packet sequence number counter per 5-tuple.

Packet Sequence Number Last Received (PSNLR)

16-bit unsigned integer. This is the PSNTP of the packet last received on the 5-tuple.

This field is initialized to 0.

Delta Time Last Received (DELTATLR)

16-bit unsigned integer. The value is set according to the scale in SCALEDTLR.

Delta Time Last Received =
(send time packet n - receive time packet (n - 1))

Delta Time Last Sent (DELTATLS)

16-bit unsigned integer. The value is set according to the scale in SCALEDTLS.

Delta Time Last Sent =
(receive time packet n - send time packet (n - 1))

3.2.2. Base Unit for Time Measurement

A time differential is always a whole number in a CPU; it is the unit specification -- hours, seconds, nanoseconds -- that determines what the numeric value means. For PDM, the base time unit is 1 attosecond (asec). This allows for a common unit and scaling of the time differential among all IP stacks and hardware implementations.

Note that PDM provides the ability to measure both time differentials that are extremely small and time differentials in a Delay/Disruption Tolerant Networking (DTN) environment where the delays may be very great. To store a time differential in just 16 bits that must range in this way will require some scaling of the time-differential value.

One issue is the conversion from the native time base in the CPU hardware of whatever device is in use to some number of attoseconds. It might seem that this will be an astronomical number, but the conversion is straightforward. It involves multiplication by an appropriate power of 10 to change the value into a number of attoseconds. Then, to scale the value so that it fits into DELTATLR or DELTATLS, the value is shifted by a number of bits, retaining the 16 high-order or most significant bits. The number of bits shifted becomes the scaling factor, stored as SCALEDTLR or SCALEDTLS, respectively. For additional information on this process, see Appendix B.

3.3. Header Placement

The PDM destination option is placed as defined in RFC 8200 [RFC8200]. There may be a choice of where to place the Destination Options header. If using Encapsulating Security Payload (ESP) mode, please see Section 3.4 of this document regarding the placement of the PDM Destination Options header.

For each IPv6 packet header, PDM MUST NOT appear more than once. However, an encapsulated packet MAY contain a separate PDM associated with each encapsulated IPv6 header.

3.4. Header Placement Using IPsec ESP Mode

IPsec ESP is defined in [RFC4303] and is widely used. Section 3.1.1 of [RFC4303] discusses the placement of Destination Options headers.

The placement of PDM is different, depending on whether ESP is used in tunnel mode or transport mode.

In the ESP case, no 5-tuple is available, as there are no port numbers. ESP flow should be identified only by using SADDR, DADDR, and PROTC. The Security Parameter Index (SPI) numbers SHOULD be ignored when considering the flow over which PDM information is measured.

3.4.1. Using ESP Transport Mode

Note that destination options may be placed before or after ESP, or both. If using PDM in ESP transport mode, PDM MUST be placed after the ESP header so as not to leak information.

3.4.2. Using ESP Tunnel Mode

Note that in both the outer set of IP headers and the inner set of IP headers, destination options may be placed before or after ESP, or both. A tunnel endpoint that creates a new packet may decide to use PDM independently of the use of PDM of the original packet to enable delay measurements between the two tunnel endpoints.

3.5. Implementation Considerations

3.5.1. PDM Activation

An implementation should provide an interface to enable or disable the use of PDM. This specification recommends having PDM off by default.

PDM MUST NOT be turned on merely if a packet is received with a PDM header. The received packet could be spoofed by another device.

3.5.2. PDM Timestamps

The PDM timestamps are intended to isolate wire time from server or host time but may necessarily attribute some host processing time to network latency.

Section 10.2 of RFC 2330 [RFC2330] ("Framework for IP Performance Metrics") describes two notions of "wire time". These notions are only defined in terms of an Internet host H observing an Internet link L at a particular location:

+ For a given IP packet P, the "wire arrival time" of P at H on L is the first time T at which any bit of P has appeared at H's observational position on L.

+ For a given IP packet P, the "wire exit time" of P at H on L is the first time T at which all the bits of P have appeared at H's observational position on L.

This specification does not define H's exact observational position on L. That is left for the deployment setups to define. However, the position where PDM timestamps are taken SHOULD be as close to the physical network interface as possible. Not all implementations will be able to achieve the ideal level of measurement.

3.6. Dynamic Configuration Options

If the PDM Destination Options header is used, then it MAY be turned on for all packets flowing through the host, applied to an upper-layer protocol (TCP, UDP, SCTP, etc.), a local port, or IP address only. These are at the discretion of the implementation.

3.7. Information Access and Storage

Measurement information provided by PDM may be made accessible for higher layers or the user itself. Similar to activating the use of PDM, the implementation may also provide an interface to indicate if received.

PDM information may be stored, if desired. If a packet with PDM information is received and the information should be stored, the upper layers may be notified. Furthermore, the implementation should define a configurable maximum lifetime after which the information can be removed as well as a configurable maximum amount of memory that should be allocated for PDM information.

4. Security Considerations

PDM may introduce some new security weaknesses.

4.1. Resource Consumption and Resource Consumption Attacks

PDM needs to calculate the deltas for time and keep track of the sequence numbers. This means that control blocks that reside in memory may be kept at the end hosts per 5-tuple.

A limit on how much memory is being used SHOULD be implemented.

Without a memory limit, any time that a control block is kept in memory, an attacker can try to misuse the control blocks to cause excessive resource consumption. This could be used to compromise the end host.

PDM is used only at the end hosts, and memory is used only at the end host and not at routers or middleboxes.

4.2. Pervasive Monitoring

Since PDM passes in the clear, a concern arises as to whether the data can be used to fingerprint the system or somehow obtain information about the contents of the payload.

Let us discuss fingerprinting of the end host first. It is possible that seeing the pattern of deltas or the absolute values could give some information as to the speed of the end host -- that is, if it is a very fast system or an older, slow device. This may be useful to the attacker. However, if the attacker has access to PDM, the attacker also has access to the entire packet and could make such a deduction based merely on the time frames elapsed between packets WITHOUT PDM.

As far as deducing the content of the payload, in terms of the application-level information such as web page, user name, user password, and so on, it appears to us that PDM is quite unhelpful in this regard. Having said that, the ability to separate wire time from processing time may potentially provide an attacker with additional information. It is conceivable that an attacker could attempt to deduce the type of application in use by noting the server time and payload length. Some encryption algorithms attempt to obfuscate the packet length to avoid just such vulnerabilities. In the future, encryption algorithms may wish to obfuscate the server

time as well.

4.3. PDM as a Covert Channel

PDM provides a set of fields in the packet that could be used to leak data. But there is no real reason to suspect that PDM would be chosen rather than another part of the payload or another extension header.

A firewall or another device could sanity-check the fields within PDM, but randomly assigned sequence numbers and delta times might be expected to vary widely. The biggest problem, though, is how an attacker would get access to PDM in the first place to leak data. The attacker would have to either compromise the end host or have a Man in the Middle (MitM). It is possible that either one could change the fields, but the other end host would then get sequence numbers and deltas that don't make any sense.

It is conceivable that someone could compromise an end host and make it start sending packets with PDM without the knowledge of the host. But, again, the bigger problem is the compromise of the end host. Once that is done, the attacker probably has better ways to leak data.

Having said that, if a PDM-aware middlebox or an implementation (destination host) detects some number of "nonsensical" sequence numbers or timing information, it could take action to block this traffic, discard it, or send an alert.

4.4. Timing Attacks

The fact that PDM can help in the separation of node processing time from network latency brings value to performance monitoring. Yet, it is this very characteristic of PDM that may be misused to make certain new types of timing attacks against protocols and implementations possible.

Depending on the nature of the cryptographic protocol used, it may be possible to leak the credentials of the device. For example, if an attacker can see that PDM is being used, then the attacker might use PDM to launch a timing attack against the keying material used by the cryptographic protocol.

An implementation may want to be sure that PDM is enabled only for certain IP addresses or only for some ports. Additionally, the implementation SHOULD require an explicit restart of monitoring after a certain time period (for example, after 1 hour) to make sure that PDM is not accidentally left on (for example, after debugging has been done).

Even so, if using PDM, a user "Consent to be Measured" SHOULD be a prerequisite for using PDM. Consent is common in enterprises and with some subscription services. The actual content of "Consent to be Measured" will differ by site, but it SHOULD make clear that the traffic is being measured for Quality of Service (QoS) and to assist in diagnostics, as well as to make clear that there may be potential risks of certain vulnerabilities if the traffic is captured during a diagnostic session.

5. IANA Considerations

IANA has registered a Destination Option Type assignment with the act bits set to 00 and the chg bit set to 0 from the "Destination Options and Hop-by-Hop Options" sub-registry of the "Internet Protocol Version 6 (IPv6) Parameters" registry [RFC2780] at <https://www.iana.org/assignments/ipv6-parameters/>.

Hex Value	Binary Value act	chg	rest	Description	Reference
0x0F	00	0	01111	Performance and Diagnostic Metrics (PDM)	RFC 8250

6. References

6.1. Normative References

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[RFC8200] Deering, S. and R. Hinden, "Internet Protocol, Version 6 (IPv6) Specification", STD 86, RFC 8200, DOI 10.17487/RFC8200, July 2017, <https://www.rfc-editor.org/info/rfc8200>.

6.2. Informative References

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[TCPM] Scheffenegger, R., Kuehlewind, M., and B. Trammell, "Encoding of Time Intervals for the TCP Timestamp Option", Work in Progress, draft-trammell-tcpm-timestamp-interval-01, July 2013.

Appendix A. Context for PDM

A.1. End-User Quality of Service (QoS)

The timing values in PDM embedded in the packet will be used to estimate QoS as experienced by an end-user device.

For many applications, the key user performance indicator is response time. When the end user is an individual, he is generally indifferent to what is happening along the network; what he really cares about is how long it takes to get a response back. But this is not just a matter of individuals' personal convenience. In many cases, rapid response is critical to the business being conducted.

Low, reliable, and acceptable response times are not just "nice to have". On many networks, the impact can be financial hardship or can endanger human life. In some cities, the emergency police contact system operates over IP; all levels of law enforcement use IP networks; transactions on our stock exchanges are settled using IP networks. The critical nature of such activities to our daily lives and financial well-being demands a simple solution to support response-time measurements.

A.2. Need for a Packet Sequence Number (PSN)

While performing network diagnostics on an end-to-end connection, it often becomes necessary to isolate the factors along the network path responsible for problems. Diagnostic data may be collected at multiple places along the path (if possible), or at the source and destination. Then, in post-collection processing, the diagnostic data corresponding to each packet at different observation points must be matched for proper measurements. A sequence number in each packet provides a sufficient basis for the matching process. If need be, the timing fields may be used along with the sequence number to ensure uniqueness.

This method of data collection along the path is of special use for determining where packet loss or packet corruption is happening.

The packet sequence number needs to be unique in the context of the session (5-tuple).

A.3. Rationale for Defined Solution

One of the important functions of PDM is to allow you to quickly dispatch the right set of diagnosticians. Within network or server latency, there may be many components. The job of the diagnostician is to rule each one out until the culprit is found.

PDM will fit into this diagnostic picture by quickly telling you how to escalate. PDM will point to either the network area or the server area. Within the server latency, PDM does not tell you whether the bottleneck is in the IP stack, the application, or buffer allocation. Within the network latency, PDM does not tell you which of the network segments or middleboxes is at fault.

What PDM does tell you is whether the problem is in the network or the server.

A.4. Use PDM with Other Headers

For diagnostics, one may want to use PDM with other headers (Layer 2, Layer 3, etc). For example, if PDM is used by a technician (or tool) looking at a packet capture, within the packet capture, they would have available to them the Layer 2 header, IP header (v6 or v4), TCP header, UDP header, ICMP header, SCTP header, or other headers. All information would be looked at together to make sense of the packet flow. The technician or processing tool could analyze, report, or ignore the data from PDM, as necessary.

For an example of how PDM can help with TCP retransmission problems, please look at Appendix C.

Appendix B. Timing Considerations

B.1. Calculations of Time Differentials

When SCALEDTLR or SCALEDTLS is used, it means that the description of the processing applies equally to SCALEDTLR and SCALEDTLS.

The time counter in a CPU is a binary whole number representing a number of milliseconds (msec), microseconds (usec), or even picoseconds (psec). Representing one of these values as attoseconds (asec) means multiplying by 10 raised to some exponent. Refer to this table of equalities:

Base value	= # of sec	= # of asec	1000s of asec
1 second	1 sec	10**18 asec	1000**6 asec
1 millisecond	10**-3 sec	10**15 asec	1000**5 asec
1 microsecond	10**-6 sec	10**12 asec	1000**4 asec
1 nanosecond	10**-9 sec	10**9 asec	1000**3 asec
1 picosecond	10**-12 sec	10**6 asec	1000**2 asec
1 femtosecond	10**-15 sec	10**3 asec	1000**1 asec

For example, if you have a time differential expressed in microseconds, since each microsecond is 10**12 asec, you would multiply your time value by 10**12 to obtain the number of attoseconds. If your time differential is expressed in nanoseconds, you would multiply by 10**9 to get the number of attoseconds.

The result is a binary value that will need to be shortened by a number of bits so it will fit into the 16-bit PDM delta field.

The next step is to divide by 2 until the value is contained in just 16 significant bits. The exponent of the value in the last column of the table is useful here; the initial scaling factor is that exponent multiplied by 10. This is the minimum number of low-order bits to be shifted out or discarded. It represents dividing the time value by 1024 raised to that exponent.

The resulting value may still be too large to fit into 16 bits but can be normalized by shifting out more bits (dividing by 2) until the value fits into the 16-bit delta field. The number of extra bits shifted out is then added to the scaling factor. The scaling factor -- the total number of low-order bits dropped -- is the SCALEDTLR or SCALEDTLS value.

For example, say an application has these start and finish timer values (hexadecimal values, in microseconds):

```
Finish:      27C849234 usec    (02:57:58.997556)
-Start:      27C83F696 usec    (02:57:58.957718)
==========   ==============    ==========================
Difference   9B9E usec         0.039838 sec or 39838 usec
```

To convert this differential value to binary attoseconds, multiply the number of microseconds by 10**12. Divide by 1024**4, or simply discard 40 bits from the right. The result is 36232, or 8D88 in hex, with a scaling factor or SCALEDTLR/SCALEDTLS value of 40.

For another example, presume the time differential is larger, say 32.311072 seconds, which is 32311072 usec. Each microsecond is 10**12 asec, so multiply by 10**12, giving the hexadecimal value 1C067FCCAE8120000. Using the initial scaling factor of 40, drop the

last 10 characters (40 bits) from that string, giving 1C067FC. This will not fit into a delta field, as it is 25 bits long. Shifting the value to the right another 9 bits results in a delta value of E033, with a resulting scaling factor of 49.

When the time-differential value is a small number, regardless of the time unit, the exponent trick given above is not useful in determining the proper scaling value. For example, if the time differential is 3 seconds and you want to convert that directly, you would follow this path:

```
3 seconds = 3*10**18 asec (decimal)
          = 29A2241AF62C0000 asec (hexadecimal)
```

If you just truncate the last 60 bits, you end up with a delta value of 2 and a scaling factor of 60, when what you really wanted was a delta value with more significant digits. The most precision with which you can store this value in 16 bits is A688, with a scaling factor of 46.

B.2. Considerations of This Time-Differential Representation

There are two considerations to be taken into account with this representation of a time differential. The first is whether there are any limitations on the maximum or minimum time differential that can be expressed using the method of a delta value and a scaling factor. The second is the amount of imprecision introduced by this method.

B.2.1. Limitations with This Encoding Method

The DELTATLS and DELTATLR fields store only the 16 most significant bits of the time-differential value. Thus, the range, excluding the scaling factor, is from 0 to 65535, or a maximum of 2**16 - 1. This method is further described in [TCPM].

The actual magnitude of the time differential is determined by the scaling factor. SCALEDTLR and SCALEDTLS are 8-bit unsigned integers,

so the scaling factor ranges from 0 to 255. The smallest number that can be represented would have a value of 1 in the delta field and a value of 0 in the associated scale field. This is the representation for 1 attosecond. Clearly, this allows PDM to measure extremely small time differentials.

On the other end of the scale, the maximum delta value is 65535, or FFFF in hexadecimal. If the maximum scale value of 255 is used, the time differential represented is 65535*2**255, which is over 3*10**55 years -- essentially, forever. So, there appears to be no real limitation to the time differential that can be represented.

B.2.2. Loss of Precision Induced by Timer Value Truncation

As PDM specifies the DELTATLR and DELTATLS values as 16-bit unsigned integers, any time that the precision is greater than those 16 bits, there will be truncation of the trailing bits, with an accompanying loss of precision in the value.

Any time-differential value smaller than 65536 asec can be stored exactly in DELTATLR or DELTATLS, because the representation of this value requires at most 16 bits.

Since the time-differential values in PDM are measured in attoseconds, the range of values that would be truncated to the same encoded value is 2**((Scale) - 1) asec.

For example, the smallest time differential that would be truncated to fit into a delta field is

```
1 0000 0000 0000 0000 = 65536 asec
```

This value would be encoded as a delta value of 8000 (hexadecimal) with a scaling factor of 1. The value

```
1 0000 0000 0000 0001 = 65537 asec
```

would also be encoded as a delta value of 8000 with a scaling factor

of 1. This actually is the largest value that would be truncated to that same encoded value. When the scale value is 1, the value range is calculated as 2**1 - 1, or 1 asec, which you can see is the difference between these minimum and maximum values.

The scaling factor is defined as the number of low-order bits truncated to reduce the size of the resulting value so it fits into a 16-bit delta field. If, for example, you had to truncate 12 bits, the loss of precision would depend on the bits you truncated. The range of these values would be

0000 0000 0000 = 0 asec

to

1111 1111 1111 = 4095 asec

So, the minimum loss of precision would be 0 asec, where the delta value exactly represents the time differential, and the maximum loss of precision would be 4095 asec. As stated above, the scaling factor of 12 means that the maximum loss of precision is 2**12 - 1 asec, or 4095 asec.

Compare this loss of precision to the actual time differential. The range of actual time-differential values that would incur this loss of precision is from

1000 0000 0000 0000 0000 0000 0000 = 2**27 asec or 134217728 asec

to

1111 1111 1111 1111 1111 1111 1111 = 2**28 - 1 asec or 268435455 asec

Granted, these are small values, but the point is that any value between these two values will have a maximum loss of precision of 4095 asec, or about 0.00305% for the first value, as encoded, and at most 0.001526% for the second. These maximum-loss percentages are consistent for all scaling values.

Appendix C. Sample Packet Flows

C.1. PDM Flow - Simple Client-Server Traffic

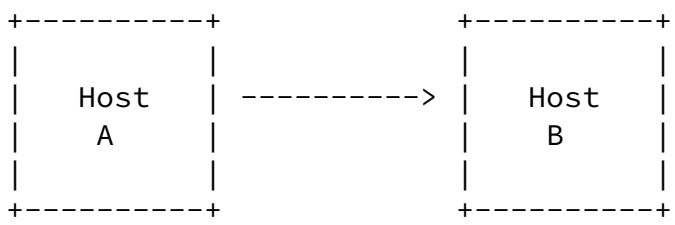
Below is a sample simple flow for PDM with one packet sent from Host A and one packet received by Host B. PDM does not require time synchronization between Host A and Host B. The calculations to derive meaningful metrics for network diagnostics are shown below each packet sent or received.

C.1.1. Step 1

Packet 1 is sent from Host A to Host B. The time for Host A is set initially to 10:00AM.

The time and packet sequence number are saved by the sender internally. The packet sequence number and delta times are sent in the packet.

Packet 1



PDM Contents:

```
PSNTP    : Packet Sequence Number This Packet:     25
PSNLR    : Packet Sequence Number Last Received:   -
DELTATLR : Delta Time Last Received:               -
SCALEDTLR: Scale of Delta Time Last Received:      0
DELTATLS : Delta Time Last Sent:                   -
SCALEDTLS: Scale of Delta Time Last Sent:          0
```

Internally, within the sender, Host A, it must keep:

Packet Sequence Number of the last packet sent: 25

Time the last packet was sent: 10:00:00

Note: The initial PSNTP from Host A starts at a random number -- in this case, 25. The time in these examples is shown in seconds for the sake of simplicity.

C.1.2. Step 2

Packet 1 is received at Host B. Its time is set to 1 hour later than Host A -- in this case, 11:00AM.

Internally, within the receiver, Host B, it must note the following:

Packet Sequence Number of the last packet received: 25
Time the last packet was received : 11:00:03

Note: This timestamp is in Host B time. It has nothing whatsoever to do with Host A time. The packet sequence number of the last packet received will become PSNLR, which will be sent out in the packet sent by Host B in the next step. The timestamp of the packet last received (as noted above) will be used as input to calculate the DELTATLR value to be sent out in the packet sent by Host B in the next step.

C.1.3. Step 3

Packet 2 is sent by Host B to Host A. Note that the initial packet sequence number (PSNTP) from Host B starts at a random number -- in this case, 12. Before sending the packet, Host B does a calculation of deltas. Since Host B knows when it is sending the packet and it knows when it received the previous packet, it can do the following calculation:

DELTATLR = send time (packet 2) - receive time (packet 1)

Note: Both the send time and the receive time are saved internally in Host B. They do not travel in the packet. Only the change in values (delta) is in the packet. This is the DELTATLR value.

Assume that within Host B we have the following:

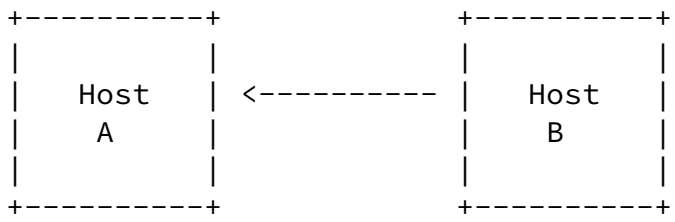
```
   Packet Sequence Number of the last packet received:     25
   Time the last packet was received:                      11:00:03
   Packet Sequence Number of this packet:                  12
   Time this packet is being sent:                         11:00:07
```

A delta value to be sent out in the packet can now be calculated. DELTATLR becomes:

```
   4 seconds = 11:00:07 - 11:00:03 = 3782DACE9D900000 asec
```

This is the derived metric: server delay. The time scaling factors must be converted; in this case, the time differential is DE0B, and the scaling factor is 2E, or 46 in decimal. Then, these values, along with the packet sequence numbers, will be sent to Host A as follows:

Packet 2



PDM Contents:

```
PSNTP    : Packet Sequence Number This Packet:    12
PSNLR    : Packet Sequence Number Last Received:  25
DELTATLR : Delta Time Last Received:              DE0B (4 seconds)
SCALEDTLR: Scale of Delta Time Last Received:     2E (46 decimal)
DELTATLS : Delta Time Last Sent:                   -
SCALEDTLS: Scale of Delta Time Last Sent:          0
```

The metric left to be calculated is the round-trip delay. This will be calculated by Host A when it receives packet 2.

C.1.4. Step 4

Packet 2 is received at Host A. Remember that its time is set to 1 hour earlier than Host B. Internally, it must note the following:

```
Packet Sequence Number of the last packet received: 12
Time the last packet was received                 : 10:00:12
```

Note: This timestamp is in Host A time. It has nothing whatsoever to do with Host B time.

So, Host A can now calculate total end-to-end time. That is:

```
End-to-End Time = Time Last Received - Time Last Sent
```

For example, packet 25 was sent by Host A at 10:00:00. Packet 12 was received by Host A at 10:00:12, so:

```
End-to-End time = 10:00:12 - 10:00:00 or 12 (server and network
round-trip delay combined).
```

```
This time may also be called "total overall Round-Trip Time
(RTT)", which includes network RTT and host response time.
```

We will call this derived metric "Delta Time Last Sent" (DELTATLS).

Round-trip delay can now be calculated. The formula is:

```
Round-trip delay =
   (Delta Time Last Sent - Delta Time Last Received)
```

Or:

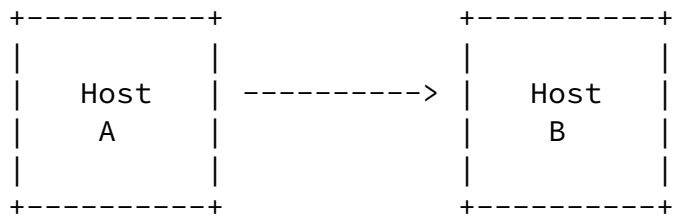
```
Round-trip delay = 12 - 4 or 8
```

At this point, the only problem is that all metrics are in Host A only and not exposed in a packet. To do that, we need a third packet.

Note: This simple example assumes one send and one receive. That is done only for purposes of explaining the function of PDM. In cases where there are multiple packets returned, one would take the time in the last packet in the sequence. The calculations of such timings and intelligent processing are the function of post-processing of the data.

C.1.5. Step 5

Packet 3 is sent from Host A to Host B.



PDM Contents:

```
PSNTP    : Packet Sequence Number This Packet:   26
PSNLR    : Packet Sequence Number Last Received: 12
DELTATLR : Delta Time Last Received:              0
SCALEDTLS: Scale of Delta Time Last Received      0
DELTATLS : Delta Time Last Sent:               A688 (scaled value)
SCALEDTLR: Scale of Delta Time Last Received:    30 (48 decimal)
```

To calculate two-way delay, any packet-capture device may look at these packets and do what is necessary.

C.2. Other Flows

What has been discussed so far is a simple flow with one packet sent and one returned. Let's look at how PDM may be useful in other types of flows.

C.2.1. PDM Flow - One-Way Traffic

The flow on a particular session may not be a send-receive paradigm. Let us consider some other situations. In the case of a one-way flow, one might see the following.

Note: The time is expressed in generic units for simplicity. That is, these values do not represent a number of attoseconds, microseconds, or any other real units of time.

Packet	Sender	PSN This Packet	PSN Last Recvd	Delta Time Last Recvd	Delta Time Last Sent

1	Server	1	0	0	0
2	Server	2	0	0	5
3	Server	3	0	0	12
4	Server	4	0	0	20

What does this mean, and how is it useful?

In a one-way flow, only the Delta Time Last Sent will be seen as used. Recall that Delta Time Last Sent is the difference between the send of one packet from a device and the next. This is a measure of throughput for the sender -- according to the sender's point of view. That is, it is a measure of how fast the application itself (with stack time included) is able to send packets.

How might this be useful? If one is having a performance issue at the client and sees that packet 2, for example, is sent after 5 time units from the server but takes 10 times that long to arrive at the destination, then one may safely conclude that there are delays in the path, other than at the server, that may be causing the delivery issue for that packet. Such delays may include the network links, middleboxes, etc.

True one-way traffic is quite rare. What people often mean by "one-way" traffic is an application such as FTP where a group of packets (for example, a TCP window size worth) is sent and the sender then waits for acknowledgment. This type of flow would actually fall into the "multiple-send" traffic model.

C.2.2. PDM Flow - Multiple-Send Traffic

Assume that two packets are sent from the server and then an ACK is sent from the client. For example, a TCP flow will do this, per RFC 1122 [RFC1122], Section 4.2.3. Packets 1 and 2 are sent from the server, and then an ACK is sent from the client. Packet 4 starts a second sequence from the server.

Packet	Sender	PSN This Packet	PSN Last Recvd	Delta Time Last Recvd	Delta Time Last Sent
1	Server	1	0	0	0

2	Server	2	0	0	5
3	Client	1	2	20	0
4	Server	3	1	10	15

How might this be used?

Notice that in packet 3, the client has a Delta Time Last Received value of 20. Recall that:

DELTATLR = send time (packet 3) - receive time (packet 2)

So, what does one know now? In this case, Delta Time Last Received is the processing time for the client to send the next packet.

How to interpret this depends on what is actually being sent. Remember that PDM is not being used in isolation; rather, it is used to supplement the fields found in other headers. Let's take two examples:

1. The client is sending a standalone TCP ACK. One would find this by looking at the payload length in the IPv6 header and the TCP Acknowledgment field in the TCP header. So, in this case, the client is taking 20 time units to send back the ACK. This may or may not be interesting.

2. The client is sending data with the packet. Again, one would find this by looking at the payload length in the IPv6 header and the TCP Acknowledgment field in the TCP header. So, in this case, the client is taking 20 time units to send back data. This may represent "User Think Time". Again, this may or may not be interesting in isolation. But if there is a performance problem receiving data at the server, then, taken in conjunction with RTT or other packet timing information, this information may be quite interesting.

Of course, one also needs to look at the PSN Last Received field to make sure of the interpretation of this data -- that is, to make sure that the Delta Time Last Received corresponds to the packet of interest.

The benefits of PDM are that such information is now available in a uniform manner for all applications and all protocols without

extensive changes required to applications.

C.2.3. PDM Flow - Multiple-Send Traffic with Errors

Let us now look at a case of how PDM may be able to help in a case of TCP retransmission and add to the information that is sent in the TCP header.

Assume that three packets are sent with each send from the server.

From the server, this is what is seen:

Pkt	Sender	PSN This Pkt	PSN Last Recvd	Delta Time Last Recvd	Delta Time Last Sent	TCP SEQ	Data Bytes
1	Server	1	0	0	0	123	100
2	Server	2	0	0	5	223	100
3	Server	3	0	0	5	333	100

The client, however, does not receive all the packets. From the client, this is what is seen for the packets sent from the server:

Pkt	Sender	PSN This Pkt	PSN Last Recvd	Delta Time Last Recvd	Delta Time Last Sent	TCP SEQ	Data Bytes
1	Server	1	0	0	0	123	100
2	Server	3	0	0	5	333	100

Let's assume that the server now retransmits the packet. (Obviously, a duplicate acknowledgment sequence for fast retransmit or a retransmit timeout would occur. To illustrate the point, these packets are being left out.)

So, if a TCP retransmission is done, then from the client, this is what is seen for the packets sent from the server:

Pkt	Sender	PSN This Pkt	PSN Last Recvd	Delta Time Last Recvd	Delta Time Last Sent	TCP SEQ	Data Bytes
1	Server	4	0	0	30	223	100

The server has resent the old packet 2 with a TCP sequence number of 223. The retransmitted packet now has a PSN This Packet value of 4.

The Delta Time Last Sent is 30 -- in other words, the time between sending the packet with a PSN of 3 and this current packet.

Let's say that packet 4 is lost again. Then, after some amount of time (RTO), the packet with a TCP sequence number of 223 is resent.

From the client, this is what is seen for the packets sent from the server:

Pkt	Sender	PSN This Pkt	PSN Last Recvd	Delta Time Last Recvd	Delta Time Last Sent	TCP SEQ	Data Bytes
1	Server	5	0	0	60	223	100

If this packet now arrives at the destination, one has a very good idea that packets exist that are being sent from the server as retransmissions and not arriving at the client. This is because the PSN of the resent packet from the server is 5 rather than 4. If we had used the TCP sequence number alone, we would never have seen this situation. The TCP sequence number in all situations is 223.

This situation would be experienced by the user of the application (the human being actually sitting somewhere) as "hangs" or long delays between packets. On large networks, to diagnose problems such as these where packets are lost somewhere on the network, one has to take multiple traces to find out exactly where.

The first thing to do is to start with doing a trace at the client and the server, so that we can see if the server sent a particular packet and the client received it. If the client did not receive it, then we start tracking back to trace points at the router right after the server and the router right before the client. Did they get these packets that the server has sent? This is a time-consuming activity.

With PDM, we can speed up the diagnostic time because we may be able to use only the trace taken at the client to see what the server is sending.

Appendix D. Potential Overhead Considerations

One might wonder about the potential overhead of PDM. First, PDM is entirely optional. That is, a site may choose to implement PDM or not, as they wish. If they are happy with the costs of PDM versus the benefits, then the choice should be theirs.

Below is a table outlining the potential overhead in terms of additional time to deliver the response to the end user for various assumed RTTs:

Bytes in Packet	RTT	Bytes Per Millisec	Bytes in PDM	New RTT	Overhead
1000	1000 milli	1	16	1016.000	16.000 milli
1000	100 milli	10	16	101.600	1.600 milli
1000	10 milli	100	16	10.160	0.160 milli
1000	1 milli	1000	16	1.016	0.016 milli

Below are two examples of actual RTTs for packets traversing large enterprise networks.

The first example is for packets going to multiple business partners:

Bytes in Packet	RTT	Bytes Per Millisec	Bytes in PDM	New RTT	Overhead
1000	17 milli	58	16	17.360	0.360 milli

The second example is for packets at a large enterprise customer within a data center. Notice that the scale is now in microseconds rather than milliseconds:

Bytes in Packet	RTT	Bytes Per Microsec	Bytes in PDM	New RTT	Overhead

1000	20 micro	50	16	20.320	0.320 micro

As with other diagnostic tools, such as packet traces, a certain amount of processing time will be required to create and process PDM. Since PDM is lightweight (has only a few variables), we expect the processing time to be minimal.

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