                       Spatial Composition of Metrics

Abstract

   This memo utilizes IP performance metrics that are applicable to both
   complete paths and sub-paths, and it defines relationships to compose
   a complete path metric from the sub-path metrics with some accuracy
   with regard to the actual metrics. This is called "spatial
   composition" in RFC 2330. The memo refers to the framework for
   metric composition, and provides background and motivation for
   combining metrics to derive others. The descriptions of several
   composed metrics and statistics follow.

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1. Introduction

    The IP Performance Metrics (IPPM) framework [RFC2330] describes two
    forms of metric composition: spatial and temporal. The composition
    framework [RFC5835] expands and further qualifies these original
    forms into three categories. This memo describes spatial
    composition, one of the categories of metrics under the umbrella of
    the composition framework.

Spatial composition encompasses the definition of performance metrics
that are applicable to a complete path, based on metrics collected on
various sub-paths.

The main purpose of this memo is to define the deterministic
functions that yield the complete path metrics using metrics of the
sub-paths. The effectiveness of such metrics is dependent on their
usefulness in analysis and applicability with practical measurement
methods.

The relationships may involve conjecture, and [RFC2330] lists four
points that the metric definitions should include:

o the specific conjecture applied to the metric and assumptions of
   the statistical model of the process being measured (if any; see
   [RFC2330], Section 12),

o a justification of the practical utility of the composition in
   terms of making accurate measurements of the metric on the path,

o a justification of the usefulness of the composition in terms of
   making analysis of the path using A-frame concepts more effective,
   and

o an analysis of how the conjecture could be incorrect.

Also, [RFC2330] gives an example using the conjecture that the delay
of a path is very nearly the sum of the delays of the exchanges and
clouds of the corresponding path digest. This example is
particularly relevant to those who wish to assess the performance of
an inter-domain path without direct measurement, and the performance
estimate of the complete path is related to the measured results for
various sub-paths instead.

Approximate functions between the sub-path and complete path metrics
are useful, with knowledge of the circumstances where the
relationships are/are not applicable. For example, we would not
expect that delay singletons from each sub-path would sum to produce
an accurate estimate of a delay singleton for the complete path
(unless all the delays were essentially constant -- very unlikely).
However, other delay statistics (based on a reasonable sample size)
may have a sufficiently large set of circumstances where they are
applicable.

1.1. Motivation

   One-way metrics defined in other RFCs (such as [RFC2679] and
   [RFC2680]) all assume that the measurement can be practically carried
   out between the source and the destination of interest. Sometimes
   there are reasons that the measurement cannot be executed from the
   source to the destination. For instance, the measurement path may
   cross several independent domains that have conflicting policies,
   measurement tools and methods, and measurement time assignment. The
   solution then may be the composition of several sub-path
   measurements. This means each domain performs the one-way
   measurement on a sub-path between two nodes that are involved in the
   complete path, following its own policy, using its own measurement
   tools and methods, and using its own measurement timing. Under the
   appropriate conditions, one can combine the sub-path one-way metric
   results to estimate the complete path one-way measurement metric with
   some degree of accuracy.

1.2. Requirements Language

   The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT",
   "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this
   document are to be interpreted as described in RFC 2119 [RFC2119].

   In this memo, the characters "<=" should be read as "less than or
   equal to" and ">=" as "greater than or equal to".

2. Scope and Application

2.1. Scope of Work

   For the primary IP Performance Metrics RFCs for loss [RFC2680], delay
   [RFC2679], and delay variation [RFC3393], this memo gives a set of
   metrics that can be composed from the same or similar sub-path
   metrics. This means that the composition function may utilize:

   o the same metric for each sub-path;

   o multiple metrics for each sub-path (possibly one that is the same
      as the complete path metric);

   o a single sub-path metric that is different from the complete path
      metric;

   o different measurement techniques like active [RFC2330], [RFC3432]
      and passive [RFC5474].

We note a possibility: using a complete path metric and all but one
sub-path metric to infer the performance of the missing sub-path,
especially when the "last" sub-path metric is missing. However, such
de-composition calculations, and the corresponding set of issues they
raise, are beyond the scope of this memo.

2.2. Application

The composition framework [RFC5835] requires the specification of the
applicable circumstances for each metric. In particular, each
section addresses whether the metric:

o Requires the same test packets to traverse all sub-paths or may
   use similar packets sent and collected separately in each
   sub-path.

o Requires homogeneity of measurement methodologies or can allow a
   degree of flexibility (e.g., active, active spatial division
   [RFC5644], or passive methods produce the "same" metric). Also,
   the applicable sending streams will be specified, such as Poisson,
   Periodic, or both.

o Needs information or access that will only be available within an
   operator's domain, or is applicable to inter-domain composition.

o Requires synchronized measurement start and stop times in all
   sub-paths or largely overlapping measurement intervals, or no
   timing requirements.

o Requires the assumption of sub-path independence with regard to
   the metric being defined/composed or other assumptions.

o Has known sources of inaccuracy/error and identifies the sources.

2.3. Incomplete Information

In practice, when measurements cannot be initiated on a sub-path (and
perhaps the measurement system gives up during the test interval),
then there will not be a value for the sub-path reported, and the
entire test result SHOULD be recorded as "undefined". This case
should be distinguished from the case where the measurement system
continued to send packets throughout the test interval, but all were
declared lost.

When a composed metric requires measurements from sub-paths A, B, and
C, and one or more of the sub-path results are undefined, then the
composed metric SHOULD also be recorded as undefined.

3. Common Specifications for Composed Metrics

   To reduce the redundant information presented in the detailed metrics
   sections that follow, this section presents the specifications that
   are common to two or more metrics. The section is organized using
   the same subsections as the individual metrics, to simplify
   comparisons.

   Also, the index variables are represented as follows:

   o m = index for packets sent.

   o n = index for packets received.

   o s = index for involved sub-paths.

3.1. Name: Type-P

   All metrics use the "Type-P" convention as described in [RFC2330].
   The rest of the name is unique to each metric.

3.1.1. Metric Parameters

   o Src, the IP address of a host.

   o Dst, the IP address of a host.

   o T, a time (start of test interval).

   o Tf, a time (end of test interval).

   o lambda, a rate in reciprocal seconds (for Poisson Streams).

   o incT, the nominal duration of inter-packet interval, first bit to
      first bit (for Periodic Streams).

   o dT, the duration of the allowed interval for Periodic Stream
      sample start times.

   o T0, a time that MUST be selected at random from the interval
      [T, T + dT] to start generating packets and taking measurements
      (for Periodic Streams).

   o TstampSrc, the wire time of the packet as measured at MP(Src)
      (measurement point at the source).

   o TstampDst, the wire time of the packet as measured at MP(Dst),
      assigned to packets that arrive within a "reasonable" time.

   o Tmax, a maximum waiting time for packets at the destination, set
      sufficiently long to disambiguate packets with long delays from
      packets that are discarded (lost); thus, the distribution of delay
      is not truncated.

   o M, the total number of packets sent between T0 and Tf.

   o N, the total number of packets received at Dst (sent between T0
      and Tf).

   o S, the number of sub-paths involved in the complete Src-Dst path.

   o Type-P, as defined in [RFC2330], which includes any field that may
      affect a packet's treatment as it traverses the network.

   In metric names, the term "<Sample>" is intended to be replaced by
   the name of the method used to define a sample of values of parameter
   TstampSrc. This can be done in several ways, including:

   1. Poisson: a pseudo-random Poisson process of rate lambda, whose
       values fall between T and Tf. The time interval between
       successive values of TstampSrc will then average 1/lambda, as per
       [RFC2330].

   2. Periodic: a Periodic stream process with pseudo-random start time
       T0 between T and dT, and nominal inter-packet interval incT, as
       per [RFC3432].

3.1.2. Definition and Metric Units

   This section is unique for every metric.

3.1.3. Discussion and Other Details

   This section is unique for every metric.

3.1.4. Statistic

   This section is unique for every metric.

3.1.5. Composition Function

   This section is unique for every metric.

3.1.6. Statement of Conjecture and Assumptions

   This section is unique for each metric. The term "ground truth" is
   frequently used in these sections and is defined in Section 4.7 of
   [RFC5835].

3.1.7. Justification of the Composition Function

   It is sometimes impractical to conduct active measurements between
   every Src-Dst pair. Since the full mesh of N measurement points
   grows as N x N, the scope of measurement may be limited by testing
   resources.

   There may be varying limitations on active testing in different parts
   of the network. For example, it may not be possible to collect the
   desired sample size in each test interval when access link speed is
   limited, because of the potential for measurement traffic to degrade
   the user traffic performance. The conditions on a low-speed access
   link may be understood well enough to permit use of a small sample
   size/rate, while a larger sample size/rate may be used on other
   sub-paths.

   Also, since measurement operations have a real monetary cost, there
   is value in re-using measurements where they are applicable, rather
   than launching new measurements for every possible source-destination
   pair.

3.1.8. Sources of Deviation from the Ground Truth

3.1.8.1. Sub-Path List Differs from Complete Path

   The measurement packets, each having source and destination addresses
   intended for collection at edges of the sub-path, may take a
   different specific path through the network equipment and links when
   compared to packets with the source and destination addresses of the
   complete path. Example sources of parallel paths include Equal Cost
   Multi-Path and parallel (or bundled) links. Therefore, the
   performance estimated from the composition of sub-path measurements
   may differ from the performance experienced by packets on the
   complete path. Multiple measurements employing sufficient sub-path
   address pairs might produce bounds on the extent of this error.

   We also note the possibility of re-routing during a measurement
   interval, as it may affect the correspondence between packets
   traversing the complete path and the sub-paths that were "involved"
   prior to the re-route.

3.1.8.2. Sub-Path Contains Extra Network Elements

   Related to the case of an alternate path described above is the case
   where elements in the measured path are unique to measurement system
   connectivity. For example, a measurement system may use a dedicated
   link to a LAN switch, and packets on the complete path do not
   traverse that link. The performance of such a dedicated link would
   be measured continuously, and its contribution to the sub-path
   metrics SHOULD be minimized as a source of error.

3.1.8.3. Sub-Paths Have Incomplete Coverage

   Measurements of sub-path performance may not cover all the network
   elements on the complete path. For example, the network exchange
   points might be excluded unless a cooperative measurement is
   conducted. In this example, test packets on the previous sub-path
   are received just before the exchange point, and test packets on the
   next sub-path are injected just after the same exchange point.
   Clearly, the set of sub-path measurements SHOULD cover all critical
   network elements in the complete path.

3.1.8.4. Absence of Route

   At a specific point in time, no viable route exists between the
   complete path source and destination. The routes selected for one or
   more sub-paths therefore differ from the complete path.
   Consequently, spatial composition may produce finite estimation of a
   ground truth metric (see Section 4.7 of [RFC5835]) between a source
   and a destination, even when the route between them is undefined.

3.1.9. Specific Cases where the Conjecture Might Fail

   This section is unique for most metrics (see the metric-specific
   sections).

   For delay-related metrics, one-way delay always depends on packet
   size and link capacity, since it is measured in [RFC2679] from first
   bit to last bit. If the size of an IP packet changes on its route
   (due to encapsulation), this can influence delay performance.
   However, the main error source may be the additional processing
   associated with encapsulation and encryption/decryption if not
   experienced or accounted for in sub-path measurements.

   Fragmentation is a major issue for composition accuracy, since all
   metrics require all fragments to arrive before proceeding, and
   fragmented complete path performance is likely to be different from
   performance with non-fragmented packets and composed metrics based on
   non-fragmented sub-path measurements.

Highly manipulated routing can cause measurement error if not
expected and compensated for. For example, policy-based MPLS routing
could modify the class of service for the sub-paths and complete
path.

3.1.10. Application of Measurement Methodology

   o The methodology SHOULD use similar packets sent and collected
      separately in each sub-path, where "similar" in this case means
      that Type-P contains as many equal attributes as possible, while
      recognizing that there will be differences. Note that Type-P
      includes stream characteristics (e.g., Poisson, Periodic).

   o The methodology allows a degree of flexibility regarding test
      stream generation (e.g., active or passive methods can produce an
      equivalent result, but the lack of control over the source,
      timing, and correlation of passive measurements is much more
      challenging).

   o Poisson and/or Periodic streams are RECOMMENDED.

   o The methodology applies to both inter-domain and intra-domain
      composition.

   o The methodology SHOULD have synchronized measurement time
      intervals in all sub-paths, but largely overlapping intervals MAY
      suffice.

   o Assumption of sub-path independence with regard to the metric
      being defined/composed is REQUIRED.

4. One-Way Delay Composed Metrics and Statistics

4.1. Name: Type-P-Finite-One-way-Delay-<Sample>-Stream

   This metric is a necessary element of delay composition metrics, and
   its definition does not formally exist elsewhere in IPPM literature.

4.1.1. Metric Parameters

   See the common parameters section (Section 3.1.1).

4.1.2. Definition and Metric Units

   Using the parameters above, we obtain the value of the Type-P-One-
   way-Delay singleton as per [RFC2679].

For each packet "[i]" that has a finite one-way delay (in other
words, excluding packets that have undefined one-way delay):

Type-P-Finite-One-way-Delay-<Sample>-Stream[i] =

   FiniteDelay[i] = TstampDst - TstampSrc

This metric is measured in units of time in seconds, expressed in
sufficiently low resolution to convey meaningful quantitative
information. For example, resolution of microseconds is usually
sufficient.

4.1.3. Discussion and Other Details

The "Type-P-Finite-One-way-Delay" metric permits calculation of the
sample mean statistic. This resolves the problem of including lost
packets in the sample (whose delay is undefined) and the issue with
the informal assignment of infinite delay to lost packets (practical
systems can only assign some very large value).

The Finite-One-way-Delay approach handles the problem of lost packets
by reducing the event space. We consider conditional statistics, and
estimate the mean one-way delay conditioned on the event that all
packets in the sample arrive at the destination (within the specified
waiting time, Tmax). This offers a way to make some valid statements
about one-way delay, at the same time avoiding events with undefined
outcomes. This approach is derived from the treatment of lost
packets in [RFC3393], and is similar to [Y.1540].

4.1.4. Statistic

All statistics defined in [RFC2679] are applicable to the finite one-
way delay, and additional metrics are possible, such as the mean (see
below).

4.2. Name: Type-P-Finite-Composite-One-way-Delay-Mean

This section describes a statistic based on the Type-P-Finite-One-
way-Delay-<Sample>-Stream metric.

4.2.1. Metric Parameters

See the common parameters section (Section 3.1.1).

4.2.2. Definition and Metric Units of the Mean Statistic

   We define

   Type-P-Finite-One-way-Delay-Mean =

```
                            N
                           ---
                    1      \
         MeanDelay = - *    >   (FiniteDelay [n])
                    N      /
                           ---
                          n = 1
```

   where all packets n = 1 through N have finite singleton delays.

   This metric is measured in units of time in seconds, expressed in
   sufficiently fine resolution to convey meaningful quantitative
   information. For example, resolution of microseconds is usually
   sufficient.

4.2.3. Discussion and Other Details

   The Type-P-Finite-One-way-Delay-Mean metric requires the conditional
   delay distribution described in Section 4.1.3.

4.2.4. Statistic

   This metric, a mean, does not require additional statistics.

4.2.5. Composition Function: Sum of Means

   The Type-P-Finite-Composite-One-way-Delay-Mean, or CompMeanDelay, for
   the complete source to destination path can be calculated from the
   sum of the mean delays of all of its S constituent sub-paths.

Then the

Type-P-Finite-Composite-One-way-Delay-Mean =

```
                                     S
                                    ---
                                     \
                 CompMeanDelay =      >    (MeanDelay [s])
                                     /
                                    ---
                                   s = 1
```

where sub-paths s = 1 to S are involved in the complete path.

4.2.6. Statement of Conjecture and Assumptions

The mean of a sufficiently large stream of packets measured on each
sub-path during the interval [T, Tf] will be representative of the
ground truth mean of the delay distribution (and the distributions
themselves are sufficiently independent), such that the means may be
added to produce an estimate of the complete path mean delay.

It is assumed that the one-way delay distributions of the sub-paths
and the complete path are continuous. The mean of multi-modal
distributions has the unfortunate property that such a value may
never occur.

4.2.7. Justification of the Composition Function

See the common section (Section 3).

4.2.8. Sources of Deviation from the Ground Truth

See the common section (Section 3).

4.2.9. Specific Cases where the Conjecture Might Fail

If any of the sub-path distributions are multi-modal, then the
measured means may not be stable, and in this case the mean will not
be a particularly useful statistic when describing the delay
distribution of the complete path.

The mean may not be a sufficiently robust statistic to produce a
reliable estimate, or to be useful even if it can be measured.

If a link contributing non-negligible delay is erroneously included
or excluded, the composition will be in error.

4.2.10. Application of Measurement Methodology

   The requirements of the common section (Section 3) apply here as
   well.

4.3. Name: Type-P-Finite-Composite-One-way-Delay-Minimum

   This section describes a statistic based on the Type-P-Finite-One-
   way-Delay-<Sample>-Stream metric, and the composed metric based on
   that statistic.

4.3.1. Metric Parameters

   See the common parameters section (Section 3.1.1).

4.3.2. Definition and Metric Units of the Minimum Statistic

   We define

   Type-P-Finite-One-way-Delay-Minimum =

              MinDelay = (FiniteDelay [j])

              such that for some index, j, where 1 <= j <= N
              FiniteDelay[j] <= FiniteDelay[n] for all n

   where all packets n = 1 through N have finite singleton delays.

   This metric is measured in units of time in seconds, expressed in
   sufficiently fine resolution to convey meaningful quantitative
   information. For example, resolution of microseconds is usually
   sufficient.

4.3.3. Discussion and Other Details

   The Type-P-Finite-One-way-Delay-Minimum metric requires the
   conditional delay distribution described in Section 4.1.3.

4.3.4. Statistic

   This metric, a minimum, does not require additional statistics.

4.3.5. Composition Function: Sum of Minima

   The Type-P-Finite-Composite-One-way-Delay-Minimum, or CompMinDelay,
   for the complete source to destination path can be calculated from
   the sum of the minimum delays of all of its S constituent sub-paths.

Then the

Type-P-Finite-Composite-One-way-Delay-Minimum =

$$CompMinDelay = \sum_{s=1}^{S} (MinDelay [s])$$

4.3.6. Statement of Conjecture and Assumptions

The minimum of a sufficiently large stream of packets measured on
each sub-path during the interval [T, Tf] will be representative of
the ground truth minimum of the delay distribution (and the
distributions themselves are sufficiently independent), such that the
minima may be added to produce an estimate of the complete path
minimum delay.

It is assumed that the one-way delay distributions of the sub-paths
and the complete path are continuous.

4.3.7. Justification of the Composition Function

See the common section (Section 3).

4.3.8. Sources of Deviation from the Ground Truth

See the common section (Section 3).

4.3.9. Specific Cases where the Conjecture Might Fail

If the routing on any of the sub-paths is not stable, then the
measured minimum may not be stable. In this case the composite
minimum would tend to produce an estimate for the complete path that
may be too low for the current path.

4.3.10. Application of Measurement Methodology

The requirements of the common section (Section 3) apply here as
well.

5. Loss Metrics and Statistics

5.1. Type-P-Composite-One-way-Packet-Loss-Empirical-Probability

5.1.1. Metric Parameters

   See the common parameters section (Section 3.1.1).

5.1.2. Definition and Metric Units

   Using the parameters above, we obtain the value of the Type-P-One-
   way-Packet-Loss singleton and stream as per [RFC2680].

   We obtain a sequence of pairs with elements as follows:

   o TstampSrc, as above.

   o L, either zero or one, where L = 1 indicates loss and L = 0
      indicates arrival at the destination within TstampSrc + Tmax.

5.1.3. Discussion and Other Details

   None.

5.1.4. Statistic: Type-P-One-way-Packet-Loss-Empirical-Probability

   Given the stream parameter M, the number of packets sent, we can
   define the Empirical Probability of Loss Statistic (Ep), consistent
   with average loss in [RFC2680], as follows:

   Type-P-One-way-Packet-Loss-Empirical-Probability =

$$Ep = \frac{1}{M} * \sum_{m=1}^{M} (L[m])$$

   where all packets m = 1 through M have a value for L.

5.1.5. Composition Function: Composition of Empirical Probabilities

   The Type-P-One-way-Composite-Packet-Loss-Empirical-Probability, or
   CompEp, for the complete source to destination path can be calculated
   by combining the Ep of all of its constituent sub-paths (Ep1, Ep2,
   Ep3, ... Epn) as

```
Type-P-Composite-One-way-Packet-Loss-Empirical-Probability =

  CompEp = 1 - {(1 - Ep1) x (1 - Ep2) x (1 - Ep3) x ... x (1 - EpS)}
```

If any Eps is undefined in a particular measurement interval,
possibly because a measurement system failed to report a value, then
any CompEp that uses sub-path s for that measurement interval is
undefined.

5.1.6. Statement of Conjecture and Assumptions

The empirical probability of loss calculated on a sufficiently large
stream of packets measured on each sub-path during the interval
[T, Tf] will be representative of the ground truth empirical loss
probability (and the probabilities themselves are sufficiently
independent), such that the sub-path probabilities may be combined to
produce an estimate of the complete path empirical loss probability.

5.1.7. Justification of the Composition Function

See the common section (Section 3).

5.1.8. Sources of Deviation from the Ground Truth

See the common section (Section 3).

5.1.9. Specific Cases where the Conjecture Might Fail

A concern for loss measurements combined in this way is that root
causes may be correlated to some degree.

For example, if the links of different networks follow the same
physical route, then a single catastrophic event like a fire in a
tunnel could cause an outage or congestion on remaining paths in
multiple networks. Here it is important to ensure that measurements
before the event and after the event are not combined to estimate the
composite performance.

Or, when traffic volumes rise due to the rapid spread of an email-
borne worm, loss due to queue overflow in one network may help
another network to carry its traffic without loss.

5.1.10. Application of Measurement Methodology

See the common section (Section 3).

6. Delay Variation Metrics and Statistics

6.1. Name: Type-P-One-way-pdv-refmin-<Sample>-Stream

   This packet delay variation (PDV) metric is a necessary element of
   Composed Delay Variation metrics, and its definition does not
   formally exist elsewhere in IPPM literature (with the exception of
   [RFC5481]).

6.1.1. Metric Parameters

   In addition to the parameters of Section 3.1.1:

   o TstampSrc[i], the wire time of packet[i] as measured at MP(Src)
      (measurement point at the source).

   o TstampDst[i], the wire time of packet[i] as measured at MP(Dst),
      assigned to packets that arrive within a "reasonable" time.

   o B, a packet length in bits.

   o F, a selection function unambiguously defining the packets from
      the stream that are selected for the packet-pair computation of
      this metric. F(current packet), the first packet of the pair,
      MUST have a valid Type-P-Finite-One-way-Delay less than Tmax (in
      other words, excluding packets that have undefined one-way delay)
      and MUST have been transmitted during the interval [T, Tf]. The
      second packet in the pair, F(min_delay packet) MUST be the packet
      with the minimum valid value of Type-P-Finite-One-way-Delay for
      the stream, in addition to the criteria for F(current packet). If
      multiple packets have equal minimum Type-P-Finite-One-way-Delay
      values, then the value for the earliest arriving packet SHOULD be
      used.

   o MinDelay, the Type-P-Finite-One-way-Delay value for F(min_delay
      packet) given above.

   o N, the number of packets received at the destination that meet the
      F(current packet) criteria.

6.1.2. Definition and Metric Units

   Using the definition above in Section 5.1.2, we obtain the value of
   Type-P-Finite-One-way-Delay-<Sample>-Stream[n], the singleton for
   each packet[i] in the stream (a.k.a. FiniteDelay[i]).

For each packet[n] that meets the F(first packet) criteria given
above: Type-P-One-way-pdv-refmin-<Sample>-Stream[n] =

    PDV[n] = FiniteDelay[n] - MinDelay

where PDV[i] is in units of time in seconds, expressed in
sufficiently fine resolution to convey meaningful quantitative
information. For example, resolution of microseconds is usually
sufficient.

6.1.3. Discussion and Other Details

This metric produces a sample of delay variation normalized to the
minimum delay of the sample. The resulting delay variation
distribution is independent of the sending sequence (although
specific FiniteDelay values within the distribution may be
correlated, depending on various stream parameters such as packet
spacing). This metric is equivalent to the IP Packet Delay Variation
parameter defined in [Y.1540].

6.1.4. Statistics: Mean, Variance, Skewness, Quantile

We define the mean PDV as follows (where all packets n = 1 through N
have a value for PDV[n]):

Type-P-One-way-pdv-refmin-Mean = MeanPDV =

$$\text{MeanPDV} = \frac{1}{N} \cdot \sum_{n=1}^{N} (PDV[n])$$

We define the variance of PDV as follows:

Type-P-One-way-pdv-refmin-Variance = VarPDV =

$$\text{VarPDV} = \frac{1}{(N-1)} \cdot \sum_{n=1}^{N} (PDV[n] - \text{MeanPDV})^2$$

We define the skewness of PDV as follows:

Type-P-One-way-pdv-refmin-Skewness = SkewPDV =

```
                  N
                 ---                                  3
                  \      /                     \
                   >    |  PDV[n] - MeanPDV  |
                  /      \                     /
                 ---
                n = 1
              ----------------------------------
               /                          \
              |                    ( 3/2 )  |
               \ (N - 1) * VarPDV          /
```

(See Appendix X of [Y.1541] for additional background information.)

We define the quantile of the PDV sample as the value where the
specified fraction of singletons is less than the given value.

6.1.5. Composition Functions

This section gives two alternative composition functions. The
objective is to estimate a quantile of the complete path delay
variation distribution. The composed quantile will be estimated
using information from the sub-path delay variation distributions.

6.1.5.1. Approximate Convolution

The Type-P-Finite-One-way-Delay-<Sample>-Stream samples from each
sub-path are summarized as a histogram with 1-ms bins representing
the one-way delay distribution.

From [STATS], the distribution of the sum of independent random
variables can be derived using the relation:

Type-P-Composite-One-way-pdv-refmin-quantile-a =

```
                        .   .
                       /   /
 P(X + Y + Z <= a) =  |   |  P(X <= a - y - z) * P(Y = y) * P(Z = z) dy dz
                       /   /
                      `   `
                     z   y
```

Note that dy and dz indicate partial integration above, and that y
and z are the integration variables. Also, the probability of an
outcome is indicated by the symbol P(outcome), where X, Y, and Z are
random variables representing the delay variation distributions of
the sub-paths of the complete path (in this case, there are three
sub-paths), and "a" is the quantile of interest.

This relation can be used to compose a quantile of interest for the
complete path from the sub-path delay distributions. The histograms
with 1-ms bins are discrete approximations of the delay
distributions.

6.1.5.2. Normal Power Approximation (NPA)

Type-P-One-way-Composite-pdv-refmin-NPA for the complete source to
destination path can be calculated by combining the statistics of all
the constituent sub-paths in the process described in [Y.1541],
Clause 8 and Appendix X.

6.1.6. Statement of Conjecture and Assumptions

The delay distribution of a sufficiently large stream of packets
measured on each sub-path during the interval [T, Tf] will be
sufficiently stationary, and the sub-path distributions themselves
are sufficiently independent, so that summary information describing
the sub-path distributions can be combined to estimate the delay
distribution of the complete path.

It is assumed that the one-way delay distributions of the sub-paths
and the complete path are continuous.

6.1.7. Justification of the Composition Function

See the common section (Section 3).

6.1.8. Sources of Deviation from the Ground Truth

In addition to the common deviations, a few additional sources exist
here. For one, very tight distributions with ranges on the order of
a few milliseconds are not accurately represented by a histogram with
1-ms bins. This size was chosen assuming an implicit requirement on
accuracy: errors of a few milliseconds are acceptable when assessing
a composed distribution quantile.

Also, summary statistics cannot describe the subtleties of an
empirical distribution exactly, especially when the distribution is
very different from a classical form. Any procedure that uses these
statistics alone may incur error.

6.1.9. Specific Cases where the Conjecture Might Fail

   If the delay distributions of the sub-paths are somehow correlated,
   then neither of these composition functions will be reliable
   estimators of the complete path distribution.

   In practice, sub-path delay distributions with extreme outliers have
   increased the error of the composed metric estimate.

6.1.10. Application of Measurement Methodology

   See the common section (Section 3).

7. Security Considerations

7.1. Denial-of-Service Attacks

   This metric requires a stream of packets sent from one host (source)
   to another host (destination) through intervening networks. This
   method could be abused for denial-of-service attacks directed at the
   destination and/or the intervening network(s).

   Administrators of source, destination, and intervening networks
   should establish bilateral or multilateral agreements regarding the
   timing, size, and frequency of collection of sample metrics. Use of
   this method in excess of the terms agreed upon between the
   participants may be cause for immediate rejection or discarding of
   packets, or other escalation procedures defined between the affected
   parties.

7.2. User Data Confidentiality

   Active use of this method generates packets for a sample, rather than
   taking samples based on user data, and does not threaten user data
   confidentiality. Passive measurement MUST restrict attention to the
   headers of interest. Since user payloads may be temporarily stored
   for length analysis, suitable precautions MUST be taken to keep this
   information safe and confidential. In most cases, a hashing function
   will produce a value suitable for payload comparisons.

7.3. Interference with the Metrics

   It may be possible to identify that a certain packet or stream of
   packets is part of a sample. With that knowledge at the destination
   and/or the intervening networks, it is possible to change the

processing of the packets (e.g., increasing or decreasing delay),
which may distort the measured performance. It may also be possible
to generate additional packets that appear to be part of the sample
metric. These additional packets are likely to perturb the results
of the sample measurement.

To discourage the kind of interference mentioned above, packet
interference checks, such as cryptographic hash, may be used.

8. IANA Considerations

Metrics defined in the IETF are typically registered in the IANA IPPM
Metrics Registry as described in the initial version of the registry
[RFC4148].

IANA has registered the following metrics in the
IANA-IPPM-METRICS-REGISTRY-MIB:

```
    ietfFiniteOneWayDelayStream OBJECT-IDENTITY
       STATUS current
       DESCRIPTION
          "Type-P-Finite-One-way-Delay-Stream"
       REFERENCE "RFC 6049, Section 4.1."
       ::= { ianaIppmMetrics 71 }


    ietfFiniteOneWayDelayMean OBJECT-IDENTITY
       STATUS current
       DESCRIPTION
          "Type-P-Finite-One-way-Delay-Mean"
       REFERENCE "RFC 6049, Section 4.2."
       ::= { ianaIppmMetrics 72 }


    ietfCompositeOneWayDelayMean OBJECT-IDENTITY
       STATUS current
       DESCRIPTION
          "Type-P-Finite-Composite-One-way-Delay-Mean"
       REFERENCE "RFC 6049, Section 4.2.5."
       ::= { ianaIppmMetrics 73 }


    ietfFiniteOneWayDelayMinimum OBJECT-IDENTITY
       STATUS current
       DESCRIPTION
          "Type-P-Finite-One-way-Delay-Minimum"
       REFERENCE "RFC 6049, Section 4.3.2."
       ::= { ianaIppmMetrics 74 }
```

```
        ietfCompositeOneWayDelayMinimum OBJECT-IDENTITY
           STATUS current
           DESCRIPTION
              "Type-P-Finite-Composite-One-way-Delay-Minimum"
           REFERENCE "RFC 6049, Section 4.3."
           ::= { ianaIppmMetrics 75 }


        ietfOneWayPktLossEmpiricProb OBJECT-IDENTITY
           STATUS current
           DESCRIPTION
              "Type-P-One-way-Packet-Loss-Empirical-Probability"
           REFERENCE "RFC 6049, Section 5.1.4"
           ::= { ianaIppmMetrics 76 }


        ietfCompositeOneWayPktLossEmpiricProb OBJECT-IDENTITY
           STATUS current
           DESCRIPTION
              "Type-P-Composite-One-way-Packet-Loss-Empirical-Probability"
           REFERENCE "RFC 6049, Section 5.1."
           ::= { ianaIppmMetrics 77 }


        ietfOneWayPdvRefminStream OBJECT-IDENTITY
           STATUS current
           DESCRIPTION
              "Type-P-One-way-pdv-refmin-Stream"
           REFERENCE "RFC 6049, Section 6.1."
           ::= { ianaIppmMetrics 78 }


        ietfOneWayPdvRefminMean OBJECT-IDENTITY
           STATUS current
           DESCRIPTION
              "Type-P-One-way-pdv-refmin-Mean"
           REFERENCE "RFC 6049, Section 6.1.4."
           ::= { ianaIppmMetrics 79 }


        ietfOneWayPdvRefminVariance OBJECT-IDENTITY
           STATUS current
           DESCRIPTION
              "Type-P-One-way-pdv-refmin-Variance"
           REFERENCE "RFC 6049, Section 6.1.4."
           ::= { ianaIppmMetrics 80 }
```

```
      ietfOneWayPdvRefminSkewness OBJECT-IDENTITY
         STATUS current
         DESCRIPTION
            "Type-P-One-way-pdv-refmin-Skewness"
         REFERENCE "RFC 6049, Section 6.1.4."
         ::= { ianaIppmMetrics 81 }


      ietfCompositeOneWayPdvRefminQtil OBJECT-IDENTITY
         STATUS current
         DESCRIPTION
            "Type-P-Composite-One-way-pdv-refmin-quantile-a"
         REFERENCE "RFC 6049, Section 6.1.5.1."
         ::= { ianaIppmMetrics 82 }


      ietfCompositeOneWayPdvRefminNPA OBJECT-IDENTITY
         STATUS current
         DESCRIPTION
            "Type-P-One-way-Composite-pdv-refmin-NPA"
         REFERENCE "RFC 6049, Section 6.1.5.2."
         ::= { ianaIppmMetrics 83 }
```

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