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Advanced Stream and Sampling Framework  
for IP Performance Metrics (IPPM)

Abstract

To obtain repeatable results in modern networks, test descriptions need an expanded stream parameter framework that also augments aspects specified as Type-P for test packets. This memo updates the IP Performance Metrics (IPPM) Framework, RFC 2330, with advanced considerations for measurement methodology and testing. The existing framework mostly assumes deterministic connectivity, and that a single test stream will represent the characteristics of the path when it is aggregated with other flows. Networks have evolved and test stream descriptions must evolve with them; otherwise, unexpected network features may dominate the measured performance. This memo describes new stream parameters for both network characterization and support of application design using IPPM metrics.

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## Table of Contents

1.	Introduction . . . . .	3
1.1.	Definition: Reactive Path Behavior . . . . .	4
1.2.	Requirements Language . . . . .	5
2.	Scope . . . . .	5
3.	New or Revised Stream Parameters . . . . .	5
3.1.	Test Packet Type-P . . . . .	6
3.1.1.	Multiple Test Packet Lengths . . . . .	7
3.1.2.	Test Packet Payload Content Optimization . . . . .	7
3.2.	Packet History . . . . .	8
3.3.	Access Technology Change . . . . .	8
3.4.	Time-Slotted Randomness Cancellation . . . . .	9
4.	Quality of Metrics and Methodologies . . . . .	10
4.1.	Revised Definition of Repeatability . . . . .	10
4.2.	Continuity No Longer an Alternative Repeatability Criterion . . . . .	11
4.3.	Metrics Should Be Actionable . . . . .	12
4.4.	It May Not Be Possible To Be Conservative . . . . .	13
4.5.	Spatial and Temporal Composition Support Unbiased Sampling . . . . .	13
4.6.	When to Truncate the Poisson Sampling Distribution . . . . .	13
5.	Conclusions . . . . .	14
6.	Security Considerations . . . . .	14
7.	Acknowledgements . . . . .	14
8.	References . . . . .	15
8.1.	Normative References . . . . .	15
8.2.	Informative References . . . . .	16

## 1. Introduction

The IETF IPPM working group first created a framework for metric development in [RFC2330]. This framework has stood the test of time and enabled development of many fundamental metrics, while only being updated once in a specific area [RFC5835].

The IPPM framework [RFC2330] generally relies on several assumptions, one of which is not explicitly stated but assumed: lightly loaded paths conform to the linear "serialization delay = packet size / capacity" equation, and they are state-less or history-less (with some exceptions, e.g., firewalls are mentioned). However, this does not hold true for many modern network technologies, such as reactive paths (those with demand-driven resource allocation) and links with time-slotted operation. Per-flow state can be observed on test packet streams, and such treatment will influence network characterization if it is not taken into account. Flow history will also affect the performance of applications and be perceived by their users.

Moreover, Sections 4 and 6.2 of [RFC2330] explicitly recommend repeatable measurement metrics and methodologies. Measurements in today's access networks illustrate that methodological guidelines of [RFC2330] must be extended to capture the reactive nature of these networks. There are proposed extensions to allow methodologies to fulfill the continuity requirement stated in Section 6.2 of [RFC2330], but it is impossible to guarantee they can do so. Practical measurements confirm that some link types exhibit distinct responses to repeated measurements with identical stimulus, i.e., identical traffic patterns. If feasible, appropriate fine-tuning of measurement traffic patterns can improve measurement continuity and repeatability for these link types as shown in [IBD].

This memo updates the IPPM framework [RFC2330] with advanced considerations for measurement methodology and testing. We note that the scope of IPPM work at the time of the publication of [RFC2330] (and during more than a decade that followed) was limited to active techniques or those that generate packet streams that are dedicated to measurement and do not monitor user traffic. This memo retains that same scope.

We stress that this update of [RFC2330] does not invalidate or require changes to the analytic metric definitions prepared in the IPPM working group to date. Rather, it adds considerations for active measurement methodologies and expands the importance of existing conventions and notions in [RFC2330], such as "packets of Type-P".

Among the evolutionary networking changes is a phenomenon we call "reactive behavior", as defined below.

### 1.1. Definition: Reactive Path Behavior

Reactive path behavior will be observable by the test packet stream as a repeatable phenomenon where packet transfer performance characteristics \*change\* according to prior observations of the packet flow of interest (at the reactive host or link). Therefore, reactive path behavior is nominally deterministic with respect to the flow of interest. Other flows or traffic load conditions may result in additional performance-affecting reactions, but these are external to the characteristics of the flow of interest.

In practice, a sender may not have absolute control of the ingress packet stream characteristics at a reactive host or link, but this does not change the deterministic reactions present there. If we measure a path, the arrival characteristics at the reactive host/link are determined by the sending characteristics and the transfer characteristics of intervening hosts and links. Identical traffic patterns at the sending host might generate different patterns at the input of the reactive host/link due to impairments in the intermediate subpath. The reactive host/link is expected to provide a deterministic response on identical input patterns (composed of all flows, including the flow of interest).

Other than the size of the payload at the layer of interest and the header itself, packet content does not influence the measurement. Reactive behavior at the IP layer is not influenced by the TCP ports in use, for example. Therefore, the indication of reactive behavior must include the layer at which measurements are instituted.

Examples include links with Active/Inactive state detectors, and hosts or links that revise their traffic serving and forwarding rates (up or down) based on packet arrival history.

Although difficult to handle from a measurement point of view, reactive paths' entities are usually designed to improve overall network performance and user experience, for example, by making capacity available to an active user. Reactive behavior may be an artifact of solutions to allocate scarce resources according to the demands of users; thus, it is an important problem to solve for measurement and other disciplines, such as application design.

## 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].

## 2. Scope

The purpose of this memo is to foster repeatable measurement results in modern networks by highlighting the key aspects of test streams and packets and making them part of the IPPM framework.

The scope is to update key sections of [RFC2330], adding considerations that will aid the development of new measurement methodologies intended for today's IP networks. Specifically, this memo describes useful stream parameters that complement the parameters discussed in Section 11.1 of [RFC2330] and the parameters described in Section 4.2 of [RFC3432] for periodic streams.

The memo also provides new considerations to update the criteria for metrics in Section 4 of [RFC2330], the measurement methodology in Section 6.2 of [RFC2330], and other topics related to the quality of metrics and methods (see Section 4).

Other topics in [RFC2330] that might be updated or augmented are deferred to future work. This includes the topics of passive and various forms of hybrid active/passive measurements.

## 3. New or Revised Stream Parameters

There are several areas where measurement methodology definition and test result interpretation will benefit from an increased understanding of the stream characteristics and the (possibly unknown) network conditions that influence the measured metrics.

1. Network treatment depends on the fullest extent on the "packet of Type-P" definition in [RFC2330], and has for some time.
  - \* State is often maintained on the per-flow basis at various points in the path, where "flows" are determined by IP and other layers. Significant treatment differences occur with the simplest of Type-P parameters: packet length. Use of multiple lengths is RECOMMENDED.
  - \* Payload content optimization (compression or format conversion) in intermediate segments breaks the convention of payload correspondence when correlating measurements are made at different points in a path.

2. Packet history (instantaneous or recent test rate or inactivity, also for non-test traffic) profoundly influences measured performance, in addition to all the Type-P parameters described in [RFC2330].
3. Access technology may change during testing. A range of transfer capacities and access methods may be encountered during a test session. When different interfaces are used, the host seeking access will be aware of the technology change, which differentiates this form of path change from other changes in network state. Section 14 of [RFC2330] addresses the possibility that a host may have more than one attachment to the network, and also that assessment of the measurement path (route) is valid for some length of time (in Sections 5 and 7 of [RFC2330]). Here, we combine these two considerations under the assumption that changes may be more frequent and possibly have greater consequences on performance metrics.
4. Paths including links or nodes with time-slotted service opportunities represent several challenges to measurement (when the service time period is appreciable):
  - \* Random/unbiased sampling is not possible beyond one such link in the path.
  - \* The above encourages a segmented approach to end-to-end measurement, as described in [RFC6049] for Network Characterization (as defined in [RFC6703]), to understand the full range of delay and delay variation on the path. Alternatively, if application performance estimation is the goal (also defined in [RFC6703]), then a stream with unbiased or known-bias properties [RFC3432] may be sufficient.
  - \* Multi-modal delay variation makes central statistics unimportant; others must be used instead.

Each of these topics is treated in detail below.

### 3.1. Test Packet Type-P

We recommend two Type-P parameters to be added to the factors that have impact on path performance measurements, namely packet length and payload type. Carefully choosing these parameters can improve measurement methodologies in their continuity and repeatability when deployed in reactive paths.

### 3.1.1. Multiple Test Packet Lengths

Many instances of network characterization using IPPM metrics have relied on a single test packet length. When testing to assess application performance or an aggregate of traffic, benchmarking methods have used a range of fixed lengths and frequently augmented fixed-size tests with a mixture of sizes, or Internet Mix (IMIX) as described in [RFC6985].

Test packet length influences delay measurements, in that the IPPM one-way delay metric [RFC2679] includes serialization time in its first-bit to last-bit timestamping requirements. However, different sizes can have a larger influence on link delay and link delay variation than serialization would explain alone. This effect can be non-linear and change the instantaneous network performance when a different size is used, or the performance of packets following the size change.

Repeatability is a main measurement methodology goal as stated in Section 6.2 of [RFC2330]. To eliminate packet length as a potential measurement uncertainty factor, successive measurements must use identical traffic patterns. In practice, a combination of random payload and random start time can yield representative results as illustrated in [IRR].

### 3.1.2. Test Packet Payload Content Optimization

The aim for efficient network resource use has resulted in deployment of server-only or client-server lossless or lossy payload compression techniques on some links or paths. These optimizers attempt to compress high-volume traffic in order to reduce network load. Files are analyzed by application-layer parsers, and parts (like comments) might be dropped. Although typically acting on HTTP or JPEG files, compression might affect measurement packets, too. In particular, measurement packets are qualified for efficient compression when they use standard plain-text payload. We note that use of transport-layer encryption will counteract the deployment of network-based analysis and may reduce the adoption of payload optimizations, however.

IPPM-conforming measurements should add packet payload content as a Type-P parameter, which can help to improve measurement determinism. Some packet payloads are more susceptible to compression than others, but optimizers in the measurement path can be out ruled by using incompressible packet payload. This payload content could be supplied by a pseudo-random sequence generator or by using part of a compressed file (e.g., a part of a ZIP compressed archive).

Optimization can go beyond the scope of one single data or measurement stream. Many more client- or network-centric optimization technologies have been proposed or standardized so far, including Robust Header Compression (ROHC) and Voice over IP aggregation as presented, for instance, in [EEAW]. Where optimization is feasible and valuable, many more of these technologies may follow. As a general observation, the more concurrent flows an intermediate host treats and the longer the paths shared by flows are, the higher becomes the incentive of hosts to aggregate flows belonging to distinct sources. Measurements should consider this potential additional source of uncertainty with respect to repeatability. Aggregation of flows in networking devices can, for instance, result in reciprocal timing and performance influence of these flows, which may exceed typical reciprocal queueing effects by orders of magnitude.

### 3.2. Packet History

Recent packet history and instantaneous data rate influence measurement results for reactive links supporting on-demand capacity allocation. Measurement uncertainty may be reduced by knowledge of measurement packet history and total host load. Additionally, small changes in history, e.g., because of lost packets along the path, can be the cause of large performance variations.

For instance, delay in reactive 3G networks like High Speed Packet Access (HSPA) depends to a large extent on the test traffic data rate. The reactive resource allocation strategy in these networks affects the uplink direction in particular. Small changes in data rate can be the reason of more than a 200% increase in delay, depending on the specific packet size. A detailed theoretical and practical analysis of Radio Resource Control (RRC) link transitions, which can cause such behavior in Universal Mobile Terrestrial System (UMTS) networks, is presented, e.g., in [RRC].

### 3.3. Access Technology Change

[RFC2330] discussed the scenario of multi-homed hosts. If hosts become aware of access technology changes (e.g., because of IP address changes or lower-layer information) and make this information available, measurement methodologies can use this information to improve measurement representativeness and relevance.

However, today's various access network technologies can present the same physical interface to the host. A host may or may not become aware when its access technology changes on such an interface. Measurements for paths that support on-demand capacity allocation are, therefore, challenging in that it is difficult to differentiate

between access technology changes (e.g., because of mobility) and reactive path behavior (e.g., because of data rate change).

#### 3.4. Time-Slotted Randomness Cancellation

Time-slotted operation of path entities -- interfaces, routers, or links -- in a network path is a particular challenge for measurements, especially if the time-slot period is substantial. The central observation as an extension to Poisson stream sampling in [RFC2330] is that the first such time-slotted component cancels unbiased measurement stream sampling. In the worst case, time-slotted operation converts an unbiased, random measurement packet stream into a periodic packet stream. Being heavily biased, these packets may interact with periodic behavior of subsequent time-slotted network entities [TSRC].

Time-slotted randomness cancellation (TSRC) sources can be found in virtually any system, network component or path, their impact on measurements being a matter of the order of magnitude when compared to the metric under observation. Examples of TSRC sources include, but are not limited to, system clock resolution, operating system ticks, time-slotted component or network operation, etc. The amount of measurement bias is determined by the particular measurement stream, relative offset between allocated time slots in subsequent path entities, delay variation in these paths, and other sources of variation. Measurement results might change over time, depending on how accurately the sending host, receiving host, and time-slotted components in the measurement path are synchronized to each other and to global time. If path segments maintain flow state, flow parameter change or flow reallocations can cause substantial variation in measurement results.

Practical measurements confirm that such interference limits delay measurement variation to a subset of theoretical value range. Measurement samples for such cases can aggregate on artificial limits, generating multi-modal distributions as demonstrated in [IRR]. In this context, the desirable measurement sample statistics differentiate between multi-modal delay distributions caused by reactive path behavior and the ones due to time-slotted interference.

Measurement methodology selection for time-slotted paths depends to a large extent on the respective viewpoint. End-to-end metrics can provide accurate measurement results for short-term sessions and low likelihood of flow state modifications. Applications or services that aim at approximating path performance for a short time interval (in the order of minutes) and expect stable path conditions should,

therefore, prefer end-to-end metrics. Here, stable path conditions refer to any kind of global knowledge concerning measurement path flow state and flow parameters.

However, if long-term forecast of time-slotted path performance is the main measurement goal, a segmented approach relying on measurement of subpath metrics is preferred. Regenerating unbiased measurement traffic at any hop can help to reveal the true range of path performance for all path segments.

#### 4. Quality of Metrics and Methodologies

[RFC6808] proposes repeatability and continuity as one of the metric and methodology properties to infer on measurement quality. Depending mainly on the set of controlled measurement parameters, measurements repeated for a specific network path using a specific methodology may or may not yield repeatable results. Challenging measurement scenarios for adequate parameter control include wireless, reactive, or time-slotted networks as discussed earlier in this document. This section presents an expanded definition of "repeatability" beyond the definition in [RFC2330] and an expanded examination of the concept of "continuity" in [RFC2330] and its limited applicability.

##### 4.1. Revised Definition of Repeatability

[RFC2330] defines repeatability in a general way:

"A methodology for a metric should have the property that it is repeatable: if the methodology is used multiple times under identical conditions, the same measurements should result in the same measurements."

The challenge is to develop this definition further, such that it becomes an objective measurable criterion (and does not depend on the concept of continuity discussed below). Fortunately, this topic has been treated in other IPPM work. In BCP 176 [RFC6576], the criteria of equivalent results was agreed as the surrogate for interoperability when assessing metric RFCs for Standards Track advancement. The criteria of equivalence were expressed as objective statistical requirements for comparison across the same implementations and independent implementations in the test plans specific to each RFC evaluated ([RFC2679] in the test plan of [RFC6808]).

The tests of [RFC6808] rely on nearly identical conditions to be present for analysis and accept that these conditions cannot be exactly identical in the production network paths used. The test

plans allow some correction factors to be applied (some statistical tests are hyper-sensitive to differences in the mean of distributions) and recognize the original findings of [RFC2330] regarding excess sample sizes.

One way to view the reliance on identical conditions is to view it as a challenge: How few parameters and path conditions need to be controlled and still produce repeatable methods/measurements?

Although the test plan in [RFC6808] documented numerical criteria for equivalence, we cannot specify the exact numerical criteria for repeatability \*in general\*. The process in the BCP [RFC6576] and statistics in [RFC6808] have been used successfully, and the numerical criteria to declare a metric repeatable should be agreed by all interested parties prior to measurement.

We revise the definition slightly, as follows:

A methodology for a metric should have the property that it is repeatable: if the methodology is used multiple times under identical conditions, the methods should produce equivalent measurement results.

#### 4.2. Continuity No Longer an Alternative Repeatability Criterion

In the original framework [RFC2330], the concept of continuity was introduced to provide a relaxed criteria for judging repeatability and was described in Section 6.2 of [RFC2330] as follows:

"...a methodology for a given metric exhibits continuity if, for small variations in conditions, it results in small variations in the resulting measurements."

Although there are conditions where metrics may exhibit continuity, there are others where this criteria would fail for both user traffic and active measurement traffic. Consider link fragmentation and the non-linear increase in delay when we increase packet size just beyond the limit of a single fragment. An active measurement packet would see the same delay increase when exceeding the fragment size.

The Bulk Transfer Capacity (BTC) [RFC3148] gives another example in Section 1, bottom of page 2:

There is also evidence that most TCP implementations exhibit non-linear performance over some portion of their operating region. It is possible to construct simple simulation examples where incremental improvements to a path (such as raising the link data rate) results in lower overall TCP throughput (or BTC) [Mat98].

Clearly, the time-slotted network elements described in Section 3.4 of this document also qualify as a new exception to the ideal of continuity.

Therefore, we deprecate continuity as an alternate criterion on metrics and prefer the more exact evaluation of repeatability instead.

#### 4.3. Metrics Should Be Actionable

The IP Performance Metrics Framework [RFC2330] includes usefulness as a metric criterion:

"...The metrics must be useful to users and providers in understanding the performance they experience or provide..."

When considering measurements as part of a maintenance process, evaluation of measurement results for a path under observation can draw attention to potential performance problems "somewhere" on the path. Anomaly detection is, therefore, an important phase and first step that already satisfies the usefulness criterion for many metrics.

This concept of usefulness can be extended, becoming a subset of what we refer to as "actionable" criterion in the following. We note that this is not the term from law.

Central to maintenance is the isolation of the root cause of reported anomalies down to a specific subpath, link or host, and metrics should support this second step as well. While detection of path anomaly may be the result of an on-going monitoring process, the second step of cause isolation consists of specific, directed on-demand measurements on components and subpaths. Metrics must support users in this directed search, becoming actionable:

Metrics must enable users and operators to understand path performance and SHOULD help to direct corrective actions when warranted, based on the measurement results.

Besides characterizing metrics, usefulness and actionable properties are also applicable to methodologies and measurements.

#### 4.4. It May Not Be Possible To Be Conservative

[RFC2330] adopts the term "conservative" for measurement methodologies for which:

"... the act of measurement does not modify, or only slightly modifies, the value of the performance metric the methodology attempts to measure."

It should be noted that this definition of "conservative" in the sense of [RFC2330] depends to a large extent on the measurement path's technology and characteristics. In particular, when deployed on reactive paths, subpaths, links or hosts conforming to the definition in Section 1.1 of this document, measurement packets can originate capacity (re)allocations. In addition, small measurement flow variations can result in other users on the same path perceiving significant variations in measurement results. Therefore:

It is not always possible for the method to be conservative.

#### 4.5. Spatial and Temporal Composition Support Unbiased Sampling

Concepts related to temporal and spatial composition of metrics in Section 9 of [RFC2330] have been extended in [RFC5835]. [RFC5835] defines multiple new types of metrics, including Spatial Composition, Temporal Aggregation, and Spatial Aggregation. So far, only the metrics for Spatial Composition have been standardized [RFC6049], providing the ability to estimate the performance of a complete path from subpath metrics. Spatial Composition aligns with the finding of [TSRC] that unbiased sampling is not possible beyond the first time-slotted link within a measurement path.

In cases where unbiased measurement for all segments of a path is not feasible due to the presence of a time-slotted link, restoring randomness of measurement samples when necessary is recommended as presented in [TSRC], in combination with Spatial Composition [RFC6049].

#### 4.6. When to Truncate the Poisson Sampling Distribution

Section 11.1.1 of [RFC2330] describes Poisson sampling, where the inter-packet send times have a Poisson distribution. A path element with reactive behavior sensitive to flow inactivity could change state if the random inter-packet time is too long.

It is recommended to truncate the tail of Poisson distribution when needed to avoid reactive element state changes.

Tail truncation has been used without issue to ensure that minimum sample sizes can be attained in a fixed-test interval.

## 5. Conclusions

Safeguarding repeatability as a key property of measurement methodologies is highly challenging and sometimes impossible in reactive paths. Measurements in paths with demand-driven allocation strategies must use a prototypical application packet stream to infer a specific application's performance. Measurement repetition with unbiased network and flow states (e.g., by rebooting measurement hosts) can help to avoid interference with periodic network behavior, with randomness being a mandatory feature for avoiding correlation with network timing.

Inferring the path performance between one measurement session or packet stream and other sessions/streams with alternate characteristics is generally discouraged with reactive paths because of the huge set of global parameters that have influence on instantaneous path performance.

## 6. Security Considerations

The security considerations that apply to any active measurement of live paths are relevant here as well. See [RFC4656] and [RFC5357].

When considering privacy of those involved in measurement or those whose traffic is measured, the sensitive information available to potential observers is greatly reduced when using active techniques that are within this scope of work. Passive observations of user traffic for measurement purposes raise many privacy issues. We refer the reader to the privacy considerations described in the Large Scale Measurement of Broadband Performance (LMAP) Framework [LMAP], which covers active and passive techniques.

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