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R. Geib, Ed.
Deutsche Telekom
A. Morton
AT&T Labs
R. Fardid
Cariden Technologies
A. Steinmitz
Deutsche Telekom

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IP Performance Metrics (IPPM) Standard Advancement Testing

Abstract

This document specifies tests to determine if multiple independent instantiations of a performance-metric RFC have implemented the specifications in the same way. This is the performance-metric equivalent of interoperability, required to advance RFCs along the Standards Track. Results from different implementations of metric RFCs will be collected under the same underlying network conditions and compared using statistical methods. The goal is an evaluation of the metric RFC itself to determine whether its definitions are clear and unambiguous to implementors and therefore a candidate for advancement on the IETF Standards Track. This document is an Internet Best Current Practice.

Status of This Memo

This memo documents an Internet Best Current Practice.

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 BCPs is available in Section 2 of RFC 5741.

Information about the current status of this document, any errata, and how to provide feedback on it may be obtained at http://www.rfc-editor.org/info/rfc6576.

Table of Contents

1. Introduction

The Internet Standards Process as updated by RFC 6410 [RFC6410] specifies that widespread deployment and use is sufficient to show interoperability as a condition for advancement to Internet Standard. The previous requirement of interoperability tests prior to advancing an RFC to the Standard maturity level specified in RFC 2026 [RFC2026] and RFC 5657 [RFC5657] has been removed. While the modified requirement is applicable to protocols, wide deployment of different measurement systems does not prove that the implementations measure metrics in a standard way. Section 5.3 of RFC 5657 [RFC5657] explicitly mentions the special case of Standards that are not "on-the-wire" protocols. While this special case is not explicitly mentioned by RFC 6410 [RFC6410], the four criteria in Section 2.2 of RFC 6410 [RFC6410] are augmented by this document for RFCs that specify performance metrics. This document takes the position that flexible metric definitions can be proven to be clear and unambiguous through tests that compare the results from independent implementations. It describes tests that infer whether metric specifications are sufficient using a definition of metric "interoperability": measuring equivalent results (in a statistical sense) under the same network conditions. The document expands on this problem and its solution.

In the case of a protocol specification, the notion of "interoperability" is reasonably intuitive -- the implementations must successfully "talk to each other", while exercising all features and options. To achieve interoperability, two implementors need to interpret the protocol specifications in equivalent ways. In the case of IP Performance Metrics (IPPM), this definition of interoperability is only useful for test and control protocols like the One-Way Active Measurement Protocol (OWAMP) [RFC4656] and the Two-Way Active Measurement Protocol (TWAMP) [RFC5357].

A metric specification RFC describes one or more metric definitions, methods of measurement, and a way to report the results of measurement. One example would be a way to test and report the one-way delay that data packets incur while being sent from one network location to another, using the One-Way Delay Metric.

In the case of metric specifications, the conditions that satisfy the "interoperability" requirement are less obvious, and there is a need for IETF agreement on practices to judge metric specification "interoperability" in the context of the IETF Standards Process. This memo provides methods that should be suitable to evaluate metric specifications for Standards Track advancement. The methods proposed here MAY be generally applicable to metric specification RFCs beyond those developed under the IPPM Framework [RFC2330].

Since many implementations of IP metrics are embedded in measurement systems that do not interact with one another (they were built before OWAMP and TWAMP), the interoperability evaluation called for in the IETF Standards Process cannot be determined by observing that independent implementations interact properly for various protocol exchanges. Instead, verifying that different implementations give statistically equivalent results under controlled measurement conditions takes the place of interoperability observations. Even when evaluating OWAMP and TWAMP RFCs for Standards Track advancement, the methods described here are useful to evaluate the measurement results because their validity would not be ascertained in protocol interoperability testing.

The Standards advancement process aims at producing confidence that the metric definitions and supporting material are clearly worded and unambiguous, or reveals ways in which the metric definitions can be revised to achieve clarity. The process also permits identification of options that were not implemented, so that they can be removed from the advancing specification. Thus, the product of this process is information about the metric specification RFC itself: determination of the specifications or definitions that are clear and unambiguous and those that are not (as opposed to an evaluation of the implementations that assist in the process).

This document defines a process to verify that implementations (or practically, measurement systems) have interpreted the metric specifications in equivalent ways and produce equivalent results.

Testing for statistical equivalence requires ensuring identical test setups (or awareness of differences) to the best possible extent. Thus, producing identical test conditions is a core goal of this memo. Another important aspect of this process is to test individual implementations against specific requirements in the metric specifications using customized tests for each requirement. These tests can distinguish equivalent interpretations of each specific requirement.

Conclusions on equivalence are reached by two measures.

First, implementations are compared against individual metric specifications to make sure that differences in implementation are minimized or at least known.

Second, a test setup is proposed ensuring identical networking conditions so that unknowns are minimized and comparisons are simplified. The resulting separate data sets may be seen as samples taken from the same underlying distribution. Using statistical methods, the equivalence of the results is verified. To illustrate

application of the process and methods defined here, evaluation of the One-Way Delay Metric [RFC2679] is provided in Appendix A. While test setups will vary with the metrics to be validated, the general methodology of determining equivalent results will not. Documents defining test setups to evaluate other metrics should be developed once the process proposed here has been agreed and approved.

The metric RFC advancement process begins with a request for protocol action accompanied by a memo that documents the supporting tests and results. The procedures of [RFC2026] are expanded in [RFC5657], including sample implementation and interoperability reports. [TESTPLAN] can serve as a template for a metric RFC report that accompanies the protocol action request to the Area Director, including a description of the test setup, procedures, results for each implementation, and conclusions.

1.1. 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. Basic Idea

The implementation of a standard compliant metric is expected to meet the requirements of the related metric specification. So, before comparing two metric implementations, each metric implementation is individually compared against the metric specification.

Most metric specifications leave freedom to implementors on non-fundamental aspects of an individual metric (or options). Comparing different measurement results using a statistical test with the assumption of identical test path and testing conditions requires knowledge of all differences in the overall test setup. Metric specification options chosen by implementors have to be documented. It is RECOMMENDED to use identical metric options for any test proposed here (an exception would be if a variable parameter of the metric definition is not configurable in one or more implementations). Calibrations specified by metric standards SHOULD be performed to further identify (and possibly reduce) potential sources of error in the test setup.

The IPPM Framework [RFC2330] expects that a "methodology for a metric should have the property that it is repeatable: if the methodology is used multiple times under identical conditions, it should result in consistent measurements". This means an implementation is expected to repeatedly measure a metric with consistent results (repeatability with the same result). Small deviations in the test setup are

expected to lead to small deviations in results only. To characterize statistical equivalence in the case of small deviations, [RFC2330] and [RFC2679] suggest to apply a 95% confidence interval. Quoting RFC 2679, "95 percent was chosen because ... a particular confidence level should be specified so that the results of independent implementations can be compared".

Two different implementations are expected to produce statistically equivalent results if they both measure a metric under the same networking conditions. Formulating in statistical terms: separate metric implementations collect separate samples from the same underlying statistical process (the same network conditions). The statistical hypothesis to be tested is the expectation that both samples do not expose statistically different properties. This requires careful test design:

- The measurement test setup must be self-consistent to the largest possible extent. To minimize the influence of the test and measurement setup on the result, network conditions and paths MUST be identical for the compared implementations to the largest possible degree. This includes both the stability and non-ambiguity of routes taken by the measurement packets. See [RFC2330] for a discussion on self-consistency.

- To minimize the influence of implementation options on the result, metric implementations SHOULD use identical options and parameters for the metric under evaluation.

- The sample size must be large enough to minimize its influence on the consistency of the test results. This consideration may be especially important if two implementations measure with different average packet transmission rates.

- The implementation with the lowest average packet transmission rate determines the smallest temporal interval for which samples can be compared.

- Repeat comparisons with several independent metric samples to avoid random indications of compatibility (or the lack of it).

The metric specifications themselves are the primary focus of evaluation, rather than the implementations of metrics. The documentation produced by the advancement process should identify which metric definitions and supporting material were found to be clearly worded and unambiguous, OR it should identify ways in which the metric specification text should be revised to achieve clarity and unified interpretation.

The process should also permit identification of options that were not implemented, so that they can be removed from the advancing specification (this is an aspect more typical of protocol advancement along the Standards Track).

Note that this document does not propose to base interoperability indications of performance-metric implementations on comparisons of individual singletons. Individual singletons may be impacted by many statistical effects while they are measured. Comparing two singletons of different implementations may result in failures with higher probability than comparing samples.

3. Verification of Conformance to a Metric Specification

This section specifies how to verify compliance of two or more IPPM implementations against a metric specification. This document only proposes a general methodology. Compliance criteria to a specific metric implementation need to be defined for each individual metric specification. The only exception is the statistical test comparing two metric implementations that are simultaneously tested. This test is applicable without metric-specific decision criteria.

Several testing options exist to compare two or more implementations:

- Use a single test lab to compare the implementations and emulate the Internet with an impairment generator.
- Use a single test lab to compare the implementations and measure across the Internet.
- Use remotely separated test labs to compare the implementations and emulate the Internet with two "identically" configured impairment generators.
- Use remotely separated test labs to compare the implementations and measure across the Internet.
- Use remotely separated test labs to compare the implementations, measure across the Internet, and include a single impairment generator to impact all measurement flows in a non-discriminatory way.

The first two approaches work, but involve higher expenses than the others (due to travel and/or shipping plus installation). For the third option, ensuring two identically configured impairment generators requires well-defined test cases and possibly identical hardware and software.

As documented in a test report [TESTPLAN], the last option was required to prove compatibility of two delay metric implementations. An impairment generator is probably required when testing compatibility of most other metrics, and it is therefore RECOMMENDED to include an impairment generator in metric test setups.

3.1. Tests of an Individual Implementation against a Metric Specification

A metric implementation is compliant with a metric specification if it supports the requirements classified as "MUST" and "REQUIRED" in the related metric specification. An implementation that implements all requirements is fully compliant with the specification, and the degree of compliance SHOULD be noted in the conclusions of the report.

Further, supported options of a metric implementation SHOULD be documented in sufficient detail to evaluate whether the specification was correctly interpreted. The documentation of chosen options should minimize (and recognize) differences in the test setup if two metric implementations are compared. Further, this documentation is used to validate or clarify the wording of the metric specification option, to remove options that saw no implementation or that are badly specified from the metric specification. This documentation SHOULD be included for all implementation-relevant specifications of a metric picked for a comparison, even those that are not explicitly marked as "MUST" or "REQUIRED" in the RFC text. This applies for the following sections of all metric specifications:

- Singleton Definition of the Metric.
- Sample Definition of the Metric.
- Statistics Definition of the Metric. As statistics are compared by the test specified here, this documentation is required even in the case that the metric specification does not contain a Statistics Definition.
- Timing- and Synchronization-related specification (if relevant for the Metric).
- Any other technical part present or missing in the metric specification, which is relevant for the implementation of the Metric.

[RFC2330] and [RFC2679] emphasize precision as an aim of IPPM metric implementations. A single IPPM-conforming implementation should under otherwise identical network conditions produce precise results for repeated measurements of the same metric.

RFC 2330 prefers the "empirical distribution function" (EDF) to describe collections of measurements. RFC 2330 determines, that "unless otherwise stated, IPPM goodness-of-fit tests are done using 5% significance". The goodness-of-fit test determines by which precision two or more samples of a metric implementation belong to the same underlying distribution (of measured network performance events). The goodness-of-fit test suggested for the metric test is the Anderson-Darling K sample test (ADK sample test, K stands for the number of samples to be compared) [ADK]. Please note that RFC 2330 and RFC 2679 apply an Anderson-Darling goodness-of-fit test, too.

The results of a repeated test with a single implementation MUST pass an ADK sample test with a confidence level of 95%. The conditions for which the ADK test has been passed with the specified confidence level MUST be documented. To formulate this differently, the requirement is to document the set of parameters with the smallest deviation at which the results of the tested metric implementation pass an ADK test with a confidence level of 95%. The minimum resolution available in the reported results from each implementation MUST be taken into account in the ADK test.

The test conditions to be documented for a passed metric test include:

- The metric resolution at which a test was passed (e.g., the resolution of timestamps).
- The parameters modified by an impairment generator.
- The impairment generator parameter settings.

3.2. Test Setup Resulting in Identical Live Network Testing Conditions

Two major issues complicate tests for metric compliance across live networks under identical testing conditions. One is the general point that metric definition implementations cannot be conveniently examined in field measurement scenarios. The other one is more broadly described as "parallelism in devices and networks", including mechanisms like those that achieve load balancing (see [RFC4928]).

This section proposes two measures to deal with both issues. Tunneling mechanisms can be used to avoid parallel processing of different flows in the network. Measuring by separate parallel probe

flows results in repeated collection of data. If both measures are combined, Wide Area Network (WAN) conditions are identical for a number of independent measurement flows, no matter what the network conditions are in detail.

Any measurement setup must be made to avoid the probing traffic itself to impede the metric measurement. The created measurement load must not result in congestion at the access link connecting the measurement implementation to the WAN. The created measurement load must not overload the measurement implementation itself, e.g., by causing a high CPU load or by causing timestamp imprecision due to unwanted queuing while transmitting or receiving test packets.

Tunneling multiple flows destined for a single physical port of a network element allows transmission of all packets via the same path. Applying tunnels to avoid undesired influence of standard routing for measurement purposes is a concept known from literature, see e.g., GRE-encapsulated multicast probing [GU-Duffield]. An existing IP-in-IP tunnel protocol can be applied to avoid Equal-Cost Multi-Path (ECMP) routing of different measurement streams if it meets the following criteria:

- Inner IP packets from different measurement implementations are mapped into a single tunnel with a single outer IP origin and destination address as well as origin and destination port numbers that are identical for all packets.

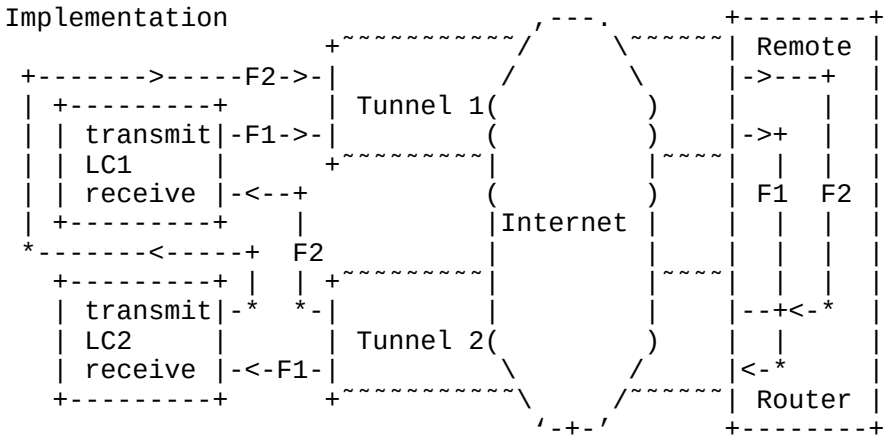
- An easily accessible tunneling protocol allows for carrying out a metric test from more test sites.

- A low operational overhead may enable a broader audience to set up a metric test with the desired properties.

- The tunneling protocol should be reliable and stable in setup and operation to avoid disturbances or influence on the test results.

- The tunneling protocol should not incur any extra cost for those interested in setting up a metric test.

An illustration of a test setup with two layer 2 tunnels and two flows between two linecards of one implementation is given in Figure 1.



For simplicity, only two linecards of one implementation and two flows F between them are shown.

Figure 1: Illustration of a Test Setup with Two Layer 2 Tunnels

Figure 2 shows the network elements required to set up layer 2 tunnels as shown by Figure 1.

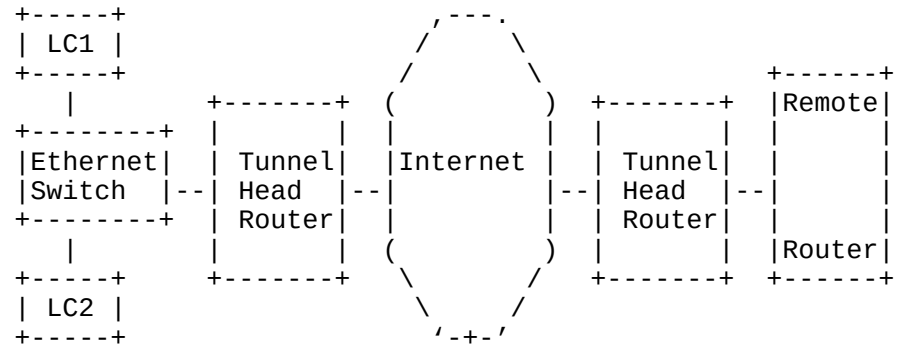


Figure 2: Illustration of a Hardware Setup to Realize the Test Setup Illustrated by Figure 1 with Layer 2 Tunnels or Pseudowires

The test setup successfully used during a delay metric test [TESTPLAN] is given as an example in Figure 3. Note that the shown setup allows a metric test between two remote sites.

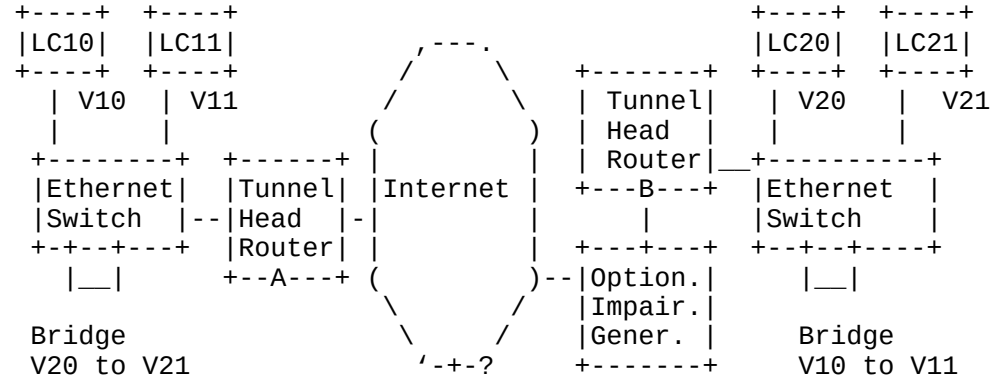


Figure 3: Example of Test Setup Successfully Used during a Delay Metic Test

In Figure 3, LC10 identifies measurement clients / linecards. V10 and the others denote VLANs. All VLANs are using the same tunnel from A to B and in the reverse direction. The remote site VLANs are U-bridged at the local site Ethernet switch. The measurement packets of site 1 travel tunnel A->B first, are U-bridged at site 2, and travel tunnel B->A second. Measurement packets of site 2 travel tunnel B->A first, are U-bridged at site 1, and travel tunnel A->B second. So, all measurement packets pass the same tunnel segments, but in different segment order.

If tunneling is applied, two tunnels MUST carry all test traffic in between the test site and the remote site. For example, if 802.1Q Virtual LANs (VLANs) are applied and the measurement streams are carried in different VLANs, the IP tunnel or pseudowires respectively are setup in physical port mode to avoid setup of pseudowires per VLAN (which may see different paths due to ECMP routing); see [RFC4448]. The remote router and the Ethernet switch shown in Figure 3 have to support 802.1Q in this setup.

The IP packet size of the metric implementation SHOULD be chosen small enough to avoid fragmentation due to the added Ethernet and tunnel headers. Otherwise, the impact of tunnel overhead on fragmentation and interface MTU size must be understood and taken into account (see [RFC4459]).

An Ethernet port mode IP tunnel carrying several 802.1Q VLANs each containing measurement traffic of a single measurement system was successfully applied when testing compatibility of two metric implementations [TESTPLAN]. Ethernet over Layer 2 Tunneling Protocol Version 3 (L2TPv3) [RFC4719] was picked for this test.

The following headers may have to be accounted for when calculating total packet length, if VLANs and Ethernet over L2TPv3 tunnels are applied:

- Ethernet 802.1Q: 22 bytes.
- L2TPv3 Header: 4-16 bytes for L2TPv3 data messages over IP; 16-28 bytes for L2TPv3 data messages over UDP.
- IPv4 Header (outer IP header): 20 bytes.
- MPLS Labels may be added by a carrier. Each MPLS Label has a length of 4 bytes. At the time of this writing, between 1 and 4 Labels seems to be a fair guess of what's expected.

The applicability of one or more of the following tunneling protocols may be investigated by interested parties if Ethernet over L2TPv3 is felt to be unsuitable: IP in IP [RFC2003] or Generic Routing Encapsulation (GRE) [RFC2784]. RFC 4928 [RFC4928] proposes measures how to avoid ECMP treatment in MPLS networks.

L2TP is a commodity tunneling protocol [RFC2661]. At the time of this writing, L2TPv3 [RFC3931] is the latest version of L2TP. If L2TPv3 is applied, software-based implementations of this protocol are not suitable for the test setup, as such implementations may cause incalculable delay shifts.

Ethernet pseudowires may also be set up on MPLS networks [RFC4448]. While there is no technical issue with this solution, MPLS interfaces are mostly found in the network provider domain. Hence, not all of the above criteria for selecting a tunneling protocol are met.

Note that setting up a metric test environment is not a plug-and-play issue. Skilled networking engineers should be consulted and involved if a setup between remote sites is preferred.

Passing or failing an ADK test with 2 samples could be a random result (note that [RFC2330] defines a sample as a set of singleton metric values produced by a measurement stream, and we continue to use this terminology here). The error margin of a statistical test is higher if the number of samples it is based on is low (the number of samples taken influences the so-called "degree of freedom" of a

statistical test, and a higher degree of freedom produces more reliable results). To pass an ADK with higher probability, the number of samples collected per implementation under identical networking conditions SHOULD be greater than 2. Hardware and load constraints may enforce an upper limit on the number of simultaneous measurement streams. The ADK test allows one to combine different samples (see Section 9 of [ADK]) and then to run a 2-sample test between combined samples. At least 4 samples per implementation captured under identical networking conditions is RECOMMENDED when comparing different metric implementations by a statistical test.

It is RECOMMENDED that tests be carried out by establishing N different parallel measurement flows. Two or three linecards per implementation serving to send or receive measurement flows should be sufficient to create 4 or more parallel measurement flows. Other options are to separate flows by DiffServ marks (without deploying any Quality of Service (QoS) in the inner or outer tunnel) or to use a single Constant Bitrate (CBR) flow and evaluate whether every n-th singleton belongs to a specific measurement flow. Note that a practical test indeed showed that ADK passed with 4 samples even if a 2-sample test failed [TESTPLAN].

Some additional guidelines to calculate and compare samples to perform a metric test are:

- Comparing different probes of a common underlying distribution in terms of metrics characterizing a communication network requires respecting the temporal nature for which the assumption of a common underlying distribution may hold. Any singletons or samples to be compared must be captured within the same time interval.

- If statistical events like rates are used to characterize measured metrics of a time interval, a minimum of 5 singletons of a relevant metric should be picked to ensure a minimum confidence into the reported value. The error margin of the determined rate depends on the number of singletons (refer to statistical textbooks on student’s t-test). As an example, any packet loss measurement interval to be compared with the results of another implementation contains at least five lost packets to have some confidence that the observed loss rate wasn’t caused by a small number of random packet drops.

- The minimum number of singletons or samples to be compared by an Anderson-Darling test should be 100 per tested metric implementation. Note that the Anderson-Darling test detects small

differences in distributions fairly well and will fail for a high number of compared results (RFC 2330 mentions an example with 8192 measurements where an Anderson-Darling test always failed).

- Generally, the Anderson-Darling test is sensitive to differences in the accuracy or bias associated with varying implementations or test conditions. These dissimilarities may result in differing averages of samples to be compared. An example may be different packet sizes, resulting in a constant delay difference between compared samples. Therefore, samples to be compared by an Anderson-Darling test MAY be calibrated by the difference of the average values of the samples. Any calibration of this kind MUST be documented in the test result.

3.3. Tests of Two or More Different Implementations against a Metric Specification

[RFC2330] expects that "a methodology for a given metric exhibits continuity if, for small variations in conditions, it results in small variations in the resulting measurements. Slightly more precisely, for every positive epsilon, there exists a positive delta, such that if two sets of conditions are within delta of each other, then the resulting measurements will be within epsilon of each other". A small variation in conditions in the context of the metric test proposed here can be seen as different implementations measuring the same metric along the same path.

IPPM metric specifications, however, allow for implementor options to the largest possible degree. It cannot be expected that two implementors allow 100% identical options in their implementations. Testers SHOULD pick the same metric measurement configurations for their systems when comparing their implementations by a metric test.

In some cases, a goodness-of-fit test may not be possible or show disappointing results. To clarify the difficulties arising from different metric implementation options, the individual options picked for every compared metric implementation should be documented as specified in Section 3.5. If the cause of the failure is a lack of specification clarity or multiple legitimate interpretations of the definition text, the text should be modified and the resulting memo proposed for consensus and (possible) advancement to Internet Standard.

The same statistical test as applicable to quantify precision of a single metric implementation must be used to compare metric result equivalence for different implementations. To document

compatibility, the smallest measurement resolution at which the compared implementations passed the ADK sample test must be documented.

For different implementations of the same metric, "variations in conditions" are reasonably expected. The ADK test comparing samples of the different implementations may result in a lower precision than the test for precision in the same-implementation comparison.

3.4. Clock Synchronization

Clock synchronization effects require special attention. Accuracy of one-way active delay measurements for any metric implementation depends on clock synchronization between the source and destination of tests. Ideally, one-way active delay measurement [RFC2679] test endpoints either have direct access to independent GPS or CDMA-based time sources or indirect access to nearby NTP primary (stratum 1) time sources, equipped with GPS receivers. Access to these time sources may not be available at all test locations associated with different Internet paths, for a variety of reasons out of scope of this document.

When secondary (stratum 2 and above) time sources are used with NTP running across the same network, whose metrics are subject to comparative implementation tests, network impairments can affect clock synchronization and distort sample one-way values and their interval statistics. Discarding sample one-way delay values for any implementation is recommended when one of the following reliability conditions is met:

- Delay is measured and is finite in one direction but not the other.

- Absolute value of the difference between the sum of one-way measurements in both directions and the round-trip measurement is greater than X% of the latter value.

Examination of the second condition requires round-trip time (RTT) measurement for reference, e.g., based on TWAMP [RFC5357] in conjunction with one-way delay measurement.

Specification of X% to strike a balance between identification of unreliable one-way delay samples and misidentification of reliable samples under a wide range of Internet path RTTs requires further study.

An IPPM-compliant metric implementation of an RFC that requires synchronized clocks is expected to provide precise measurement results.

IF an implementation publishes a specification of its precision, such as "a precision of 1 ms (+/- 500 us) with a confidence of 95%", then the specification should be met over a useful measurement duration. For example, if the metric is measured along an Internet path that is stable and not congested, then the precision specification should be met over durations of an hour or more.

3.5. Recommended Metric Verification Measurement Process

In order to meet their obligations under the IETF Standards Process, the IESG must be convinced that each metric specification advanced to Internet Standard status is clearly written, that there are a sufficient number of verified equivalent implementations, and that options that have been implemented are documented.

In the context of this document, metrics are designed to measure some characteristic of a data network. An aim of any metric definition should be that it is specified in a way that can reliably measure the specific characteristic in a repeatable way across multiple independent implementations.

Each metric, statistic, or option of those to be validated MUST be compared against a reference measurement or another implementation as specified in this document.

Finally, the metric definitions, embodied in the text of the RFCs, are the objects that require evaluation and possible revision in order to advance to Internet Standard.

IF two (or more) implementations do not measure an equivalent metric as specified by this document,

AND sources of measurement error do not adequately explain the lack of agreement,

THEN the details of each implementation should be audited along with the exact definition text to determine if there is a lack of clarity that has caused the implementations to vary in a way that affects the correspondence of the results.

IF there was a lack of clarity or multiple legitimate interpretations of the definition text,

THEN the text should be modified and the resulting memo proposed for consensus and (possible) advancement along the Standards Track.

Finally, all the findings MUST be documented in a report that can support advancement to Internet Standard, as described here (similar to the reports described in [RFC5657]). The list of measurement devices used in testing satisfies the implementation requirement, while the test results provide information on the quality of each specification in the metric RFC (the surrogate for feature interoperability).

The complete process of advancing a metric specification to a Standard as defined by this document is illustrated in Figure 4.

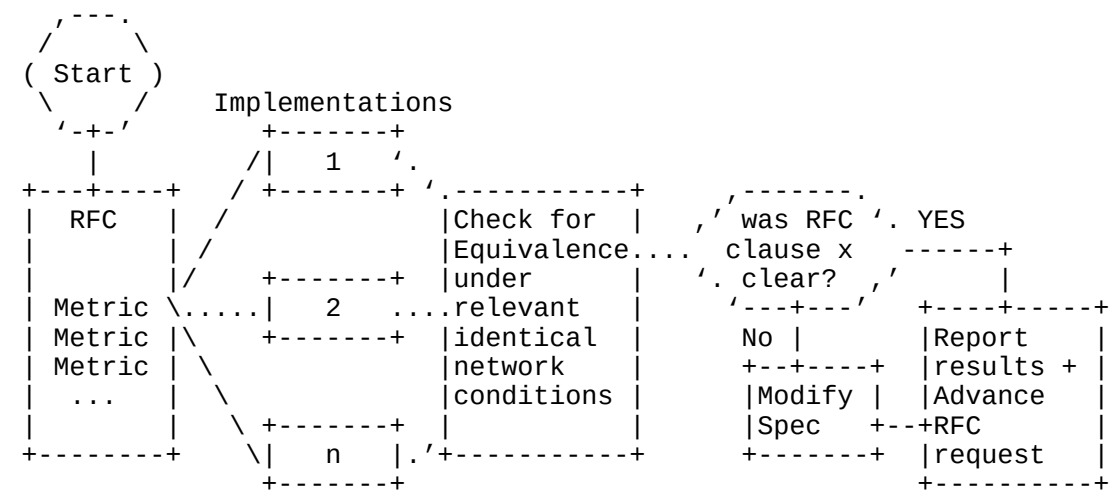


Figure 4: Illustration of the Metric Standardization Process

Any recommendation for the advancement of a metric specification MUST be accompanied by an implementation report. The implementation report needs to include the tests performed, the applied test setup, the specific metrics in the RFC, and reports of the tests performed with two or more implementations. The test plan needs to specify the precision reached for each measured metric and thus define the meaning of "statistically equivalent" for the specific metrics being tested.

Ideally, the test plan would co-evolve with the development of the metric, since that's when participants have the clearest context in their minds regarding the different subtleties that can arise.

In particular, the implementation report MUST include the following at minimum:

- The metric compared and the RFC specifying it. This includes statements as required by Section 3.1 ("Tests of an Individual Implementation against a Metric Specification") of this document.

- The measurement configuration and setup.

- A complete specification of the measurement stream (mean rate, statistical distribution of packets, packet size or mean packet size, and their distribution), Differentiated Services Code Point (DSCP), and any other measurement stream properties that could result in deviating results. Deviations in results can also be caused if chosen IP addresses and ports of different implementations result in different layer 2 or layer 3 paths due to operation of Equal Cost Multi-Path routing in an operational network.

- The duration of each measurement to be used for a metric validation, the number of measurement points collected for each metric during each measurement interval (i.e., the probe size), and the level of confidence derived from this probe size for each measurement interval.

- The result of the statistical tests performed for each metric validation as required by Section 3.3 ("Tests of Two or More Different Implementations against a Metric Specification") of this document.

- A parameterization of laboratory conditions and applied traffic and network conditions allowing reproduction of these laboratory conditions for readers of the implementation report.

- The documentation helping to improve metric specifications defined by this section.

All of the tests for each set SHOULD be run in a test setup as specified in Section 3.2 ("Test Setup Resulting in Identical Live Network Testing Conditions".

If a different test setup is chosen, it is recommended to avoid effects falsifying results of validation measurements caused by real data networks (like parallelism in devices and networks). Data networks may forward packets differently in the case of:

- Different packet sizes chosen for different metric implementations. A proposed countermeasure is selecting the same packet size when validating results of two samples or a sample against an original distribution.

- Selection of differing IP addresses and ports used by different metric implementations during metric validation tests. If ECMP is applied on the IP or MPLS level, different paths can result (note that it may be impossible to detect an MPLS ECMP path from an IP endpoint). A proposed countermeasure is to connect the measurement equipment to be compared by a NAT device or establish a single tunnel to transport all measurement traffic. The aim is to have the same IP addresses and port for all measurement packets or to avoid ECMP-based local routing diversion by using a layer 2 tunnel.

- Different IP options.

- Different DSCP.

- If the N measurements are captured using sequential measurements instead of simultaneous ones, then the following factors come into play: time varying paths and load conditions.

3.6. Proposal to Determine an Equivalence Threshold for Each Metric Evaluated

This section describes a proposal for maximum error of equivalence, based on performance comparison of identical implementations. This comparison may be useful for both ADK and non-ADK comparisons.

Each metric is tested by two or more implementations (cross-implementation testing).

Each metric is also tested twice simultaneously by the *same* implementation, using different Src/Dst Address pairs and other differences such that the connectivity differences of the cross-implementation tests are also experienced and measured by the same implementation.

Comparative results for the same implementation represent a bound on cross-implementation equivalence. This should be particularly useful when the metric does *not* produce a continuous distribution of singleton values, such as with a loss metric or a duplication metric. Appendix A indicates how the ADK will work for one-way delay and should be likewise applicable to distributions of delay variation.

Appendix B discusses two possible ways to perform the ADK analysis: the R statistical language [Rtool] with ADK package [Radk] and C++ code.

Conclusion: the implementation with the largest difference in homogeneous comparison results is the lower bound on the equivalence threshold, noting that there may be other systematic errors to account for when comparing implementations.

Thus, when evaluating equivalence in cross-implementation results:

Maximum_Error = Same_Implementation_Error + Systematic_Error

and only the systematic error need be decided beforehand.

In the case of ADK comparison, the largest same-implementation resolution of distribution equivalence can be used as a limit on cross-implementation resolutions (at the same confidence level).

4. Acknowledgements

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5. Contributors

Scott Bradner, Vern Paxson, and Allison Mankin drafted [METRICTEST], and major parts of it are included in this document.

6. Security Considerations

This memo does not raise any specific security issues.

7. References

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Appendix A. An Example on a One-Way Delay Metric Validation

The text of this appendix is not binding. It is an example of what parts of a One-Way Delay Metric test could look like.

A.1. Compliance to Metric Specification Requirements

One-Way Delay, Loss Threshold, RFC 2679

This test determines if implementations use the same configured maximum waiting time delay from one measurement to another under different delay conditions and correctly declare packets arriving in excess of the waiting time threshold as lost. See Sections 3.5 (3rd bullet point) and 3.8.2 of [RFC2679].

(1) Configure a path with 1-second one-way constant delay.

(2) Measure one-way delay with 2 or more implementations, using identical waiting time thresholds for loss set at 2 seconds.

(3) Configure the path with 3-second one-way delay.

(4) Repeat measurements.

(5) Observe that the increase measured in step 4 caused all packets to be declared lost and that all packets that arrive successfully in step 2 are assigned a valid one-way delay.

One-Way Delay, First Bit to Last Bit, RFC 2679

This test determines if implementations register the same relative increase in delay from one measurement to another under different delay conditions. This test tends to cancel the sources of error that may be present in an implementation. See Section 3.7.2 of [RFC2679] and Section 10.2 of [RFC2330].

(1) Configure a path with X ms one-way constant delay and ideally include a low-speed link.

(2) Measure one-way delay with 2 or more implementations, using identical options and equal size small packets (e.g., 100 octet IP payload).

(3) Maintain the same path with X ms one-way delay.

(4) Measure one-way delay with 2 or more implementations, using identical options and equal size large packets (e.g., 1500 octet IP payload).

(5) Observe that the increase measured in steps 2 and 4 is equivalent to the increase in ms expected due to the larger serialization time for each implementation. Most of the measurement errors in each system should cancel, if they are stationary.

One-Way Delay, RFC 2679

This test determines if implementations register the same relative increase in delay from one measurement to another under different delay conditions. This test tends to cancel the sources of error that may be present in an implementation. This test is intended to evaluate measurements in Sections 3 and 4 of [RFC2679].

(1) Configure a path with X ms one-way constant delay.

(2) Measure one-way delay with 2 or more implementations, using identical options.

(3) Configure the path with X+Y ms one-way delay.

(4) Repeat measurements.

(5) Observe that the increase measured in steps 2 and 4 is ~Y ms for each implementation. Most of the measurement errors in each system should cancel, if they are stationary.

Error Calibration, RFC 2679

This is a simple check to determine if an implementation reports the error calibration as required in Section 4.8 of [RFC2679]. Note that the context (Type-P) must also be reported.

A.2. Examples Related to Statistical Tests for One-Way Delay

A one-way delay measurement may pass an ADK test with a timestamp result of 1 ms. The same test may fail if timestamps with a resolution of 100 microseconds are evaluated. The implementation is then conforming to the metric specification up to a timestamp resolution of 1 ms.

Let’s assume another one-way delay measurement comparison between implementation 1 probing with a frequency of 2 probes per second and implementation 2 probing at a rate of 2 probes every 3 minutes. To ensure reasonable confidence in results, sample metrics are calculated from at least 5 singletons per compared time interval. This means that sample delay values are calculated for each system for identical 6-minute intervals for the duration of the whole test.

Per 6-minute interval, the sample metric is calculated from 720 singletons for implementation 1 and from 6 singletons for implementation 2. Note that if outliers are not filtered, moving averages are an option for an evaluation too. The minimum move of an averaging interval is three minutes in this example.

The data in Table 1 may result from measuring one-way delay with implementation 1 (see column Implemnt_1) and implementation 2 (see column Implemnt_2). Each data point in the table represents a (rounded) average of the sampled delay values per interval. The resolution of the clock is one micro-second. The difference in the delay values may result, e.g., from different probe packet sizes.

Implemnt_1	Implemnt_2	Implemnt_2 - Delta_Averages
5000	6549	4997
5008	6555	5003
5012	6564	5012
5015	6565	5013
5019	6568	5016
5022	6570	5018
5024	6573	5021
5026	6575	5023
5027	6577	5025
5029	6580	5028
5030	6585	5033
5032	6586	5034
5034	6587	5035
5036	6588	5036
5038	6589	5037
5039	6591	5039
5041	6592	5040
5043	6599	5047
5046	6606	5054
5054	6612	5060

Table 1

Average values of sample metrics captured during identical time intervals are compared. This excludes random differences caused by differing probing intervals or differing temporal distance of singletons resulting from their Poisson-distributed sending times.

In the example, 20 values have been picked (note that at least 100 values are recommended for a single run of a real test). Data must be ordered by ascending rank. The data of Implemnt_1 and Implemnt_2 as shown in the first two columns of Table 1 clearly fails an ADK test with 95% confidence.

The results of Implemnt_2 are now reduced by the difference of the averages of column 2 (rounded to 6581 us) and column 1 (rounded to 5029 us), which is 1552 us. The result may be found in column 3 of Table 1. Comparing column 1 and column 3 of the table by an ADK test shows that the data contained in these columns passes an ADK test with 95% confidence.

Comment: Extensive averaging was used in this example because of the vastly different sampling frequencies. As a result, the distributions compared do not exactly align with a metric in [RFC2679] but illustrate the ADK process adequately.

Appendix B. Anderson-Darling K-sample Reference and 2 Sample C++ Code

There are many statistical tools available, and this appendix describes two that are familiar to the authors.

The "R tool" is a language and command-line environment for statistical computing and plotting [Rtool]. With the optional "adk" package installed [Radk], it can perform individual and combined sample ADK computations. The user must consult the package documentation and the original paper [ADK] to interpret the results, but this is as it should be.

The C++ code below will perform an AD2-sample comparison when compiled and presented with two column vectors in a file (using white space as separation). This version contains modifications made by Wes Eddy in Sept 2011 to use the vectors and run as a stand-alone module. The status of the comparison can be checked on the command line with "$ echo $?" or the last line can be replaced with a printf statement for adk_result instead.

```
/*

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   as authors of the code.  All rights reserved.

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```

```
  */

  /* Routines for computing the Anderson-Darling 2 sample
  * test statistic.
  *
  * Implemented based on the description in
  * "Anderson-Darling K Sample Test" Heckert, Alan and
  * Filliben, James, editors, Dataplot Reference Manual,
  * Chapter 15 Auxiliary, NIST, 2004.
  * Official Reference by 2010
  * Heckert, N. A. (2001).  Dataplot website at the
  * National Institute of Standards and Technology:
  * http://www.itl.nist.gov/div898/software/dataplot.html/
  * June 2001.
 */

 #include <iostream>
 #include <fstream>
 #include <vector>
 #include <sstream>

 using namespace std;

 int main() {
    vector<double> vec1, vec2;
    double adk_result;
    static int k, val_st_z_samp1, val_st_z_samp2,
               val_eq_z_samp1, val_eq_z_samp2,
               j, n_total, n_sample1, n_sample2, L,
               max_number_samples, line, maxnumber_z;
    static int column_1, column_2;
    static double adk, n_value, z, sum_adk_samp1,
                  sum_adk_samp2, z_aux;
    static double H_j, F1j, hj, F2j, denom_1_aux, denom_2_aux;
    static bool next_z_sample2, equal_z_both_samples;
    static int stop_loop1, stop_loop2, stop_loop3,old_eq_line2,
               old_eq_line1;

    static double adk_criterium = 1.993;

    /* vec1 and vec2 to be initialized with sample 1 and
     * sample 2 values in ascending order */
    while (!cin.eof()) {
       double f1, f2;
       cin >> f1;
       cin >> f2;
       vec1.push_back(f1);
       vec2.push_back(f2);
```

```
    }

    k = 2;
    n_sample1 = vec1.size() - 1;
    n_sample2 = vec2.size() - 1;

    // -1 because vec[0] is a dummy value
    n_total = n_sample1 + n_sample2;

    /* value equal to the line with a value = zj in sample 1.
     * Here j=1, so the line is 1.
     */
    val_eq_z_samp1 = 1;

    /* value equal to the line with a value = zj in sample 2.
     * Here j=1, so the line is 1.
     */
    val_eq_z_samp2 = 1;

    /* value equal to the last line with a value < zj
     * in sample 1.  Here j=1, so the line is 0.
     */
    val_st_z_samp1 = 0;

    /* value equal to the last line with a value < zj
     * in sample 1.  Here j=1, so the line is 0.
     */
    val_st_z_samp2 = 0;

    sum_adk_samp1 = 0;
    sum_adk_samp2 = 0;
    j = 1;

    // as mentioned above, j=1
    equal_z_both_samples = false;

    next_z_sample2 = false;

    //assuming the next z to be of sample 1
    stop_loop1 = n_sample1 + 1;

    // + 1 because vec[0] is a dummy, see n_sample1 declaration
    stop_loop2 = n_sample2 + 1;
    stop_loop3 = n_total + 1;

    /* The required z values are calculated until all values
     * of both samples have been taken into account.  See the
     * lines above for the stoploop values.  Construct required
```

```
     * to avoid a mathematical operation in the while condition.
     */
    while (((stop_loop1 > val_eq_z_samp1)
           || (stop_loop2 > val_eq_z_samp2)) && stop_loop3 > j)
    {
      if(val_eq_z_samp1 < n_sample1+1)
      {
     /* here, a preliminary zj value is set.
      * See below how to calculate the actual zj.
      */
            z = vec1[val_eq_z_samp1];

     /* this while sequence calculates the number of values
      * equal to z.
      */
            while ((val_eq_z_samp1+1 < n_sample1)
                    && z == vec1[val_eq_z_samp1+1] )
                    {
                    val_eq_z_samp1++;
                    }
            }
            else
            {
            val_eq_z_samp1 = 0;
            val_st_z_samp1 = n_sample1;

    // this should be val_eq_z_samp1 - 1 = n_sample1
            }

    if(val_eq_z_samp2 < n_sample2+1)
            {
            z_aux = vec2[val_eq_z_samp2];;

    /* this while sequence calculates the number of values
     * equal to z_aux
     */

            while ((val_eq_z_samp2+1 < n_sample2)
                    && z_aux == vec2[val_eq_z_samp2+1] )
                    {
                    val_eq_z_samp2++;
                    }

    /* the smaller of the two actual data values is picked
     * as the next zj.
     */

       if(z > z_aux)
```

```
                    {
                    z = z_aux;
                    next_z_sample2 = true;
                    }
             else
                    {
                    if (z == z_aux)
                    {
                    equal_z_both_samples = true;
                    }

    /* This is the case if the last value of column1 is
     * smaller than the remaining values of column2.
     */
                   if (val_eq_z_samp1 == 0)
                    {
                    z = z_aux;
                    next_z_sample2 = true;
                    }
                }
            }
           else
              {
            val_eq_z_samp2 = 0;
            val_st_z_samp2 = n_sample2;

    // this should be val_eq_z_samp2 - 1 = n_sample2

            }

     /* in the following, sum j = 1 to L is calculated for
      * sample 1 and sample 2.
      */
           if (equal_z_both_samples)
              {

              /* hj is the number of values in the combined sample
               * equal to zj
               */
                   hj = val_eq_z_samp1 - val_st_z_samp1
                  + val_eq_z_samp2 - val_st_z_samp2;

              /* H_j is the number of values in the combined sample
               * smaller than zj plus one half the number of
               * values in the combined sample equal to zj
               * (that's hj/2).
               */
                  H_j = val_st_z_samp1 + val_st_z_samp2
```

```
                    + hj / 2;

               /* F1j is the number of values in the 1st sample
                * that are less than zj plus one half the number
                * of values in this sample that are equal to zj.
                */

                  F1j = val_st_z_samp1 + (double)
                      (val_eq_z_samp1 - val_st_z_samp1) / 2;

               /* F2j is the number of values in the 1st sample
                * that are less than zj plus one half the number
                * of values in this sample that are equal to zj.
                */
                  F2j = val_st_z_samp2 + (double)
                     (val_eq_z_samp2 - val_st_z_samp2) / 2;

               /* set the line of values equal to zj to the
                * actual line of the last value picked for zj.
                */
                  val_st_z_samp1 = val_eq_z_samp1;

               /* Set the line of values equal to zj to the actual
                * line of the last value picked for zj of each
                * sample.  This is required as data smaller than zj
                * is accounted differently than values equal to zj.
                */
                  val_st_z_samp2 = val_eq_z_samp2;

               /* next the lines of the next values z, i.e., zj+1
                * are addressed.
                */
                 val_eq_z_samp1++;

               /* next the lines of the next values z, i.e.,
                * zj+1 are addressed
                */
                  val_eq_z_samp2++;
                  }
          else
                  {

               /* the smaller z value was contained in sample 2;
                * hence, this value is the zj to base the following
                * calculations on.
                */
                            if (next_z_sample2)
                            {
```

```
/* hj is the number of values in the combined
 * sample equal to zj; in this case, these are
 * within sample 2 only.
 */
             hj = val_eq_z_samp2 - val_st_z_samp2;

/* H_j is the number of values in the combined sample
 * smaller than zj plus one half the number of
 * values in the combined sample equal to zj
 * (that's hj/2).
 */
                H_j = val_st_z_samp1 + val_st_z_samp2
               + hj / 2;

/* F1j is the number of values in the 1st sample that
 * are less than zj plus one half the number of values in
 * this sample that are equal to zj.
 * As val_eq_z_samp2 < val_eq_z_samp1, these are the
 * val_st_z_samp1 only.
 */
             F1j = val_st_z_samp1;

/* F2j is the number of values in the 1st sample that
 * are less than zj plus one half the number of values in
 * this sample that are equal to zj.  The latter are from
 * sample 2 only in this case.
 */

     F2j = val_st_z_samp2 + (double)
          (val_eq_z_samp2 - val_st_z_samp2) / 2;

/* Set the line of values equal to zj to the actual line
 * of the last value picked for zj of sample 2 only in
 * this case.
 */
                 val_st_z_samp2 = val_eq_z_samp2;

/* next the line of the next value z, i.e., zj+1 is
 * addressed.  Here, only sample 2 must be addressed.
 */

     val_eq_z_samp2++;
                 if (val_eq_z_samp1 == 0)
                 {
                 val_eq_z_samp1 = stop_loop1;
                 }
             }
```

```
    /* the smaller z value was contained in sample 2;
     * hence, this value is the zj to base the following
     * calculations on.
     */

                 else
                 {

    /* hj is the number of values in the combined
     * sample equal to zj; in this case, these are
     * within sample 1 only.
     */
                 hj = val_eq_z_samp1 - val_st_z_samp1;

    /* H_j is the number of values in the combined
     * sample smaller than zj plus one half the number
     * of values in the combined sample equal to zj
     * (that's hj/2).
     */

          H_j = val_st_z_samp1 + val_st_z_samp2
                + hj / 2;

    /* F1j is the number of values in the 1st sample that
     * are less than zj plus; in this case, these are within
     * sample 1 only one half the number of values in this
     * sample that are equal to zj.  The latter are from
     * sample 1 only in this case.
     */

          F1j = val_st_z_samp1 + (double)
               (val_eq_z_samp1 - val_st_z_samp1) / 2;

    /* F2j is the number of values in the 1st sample that
     * are less than zj plus one half the number of values
     * in this sample that are equal to zj.  As
     * val_eq_z_samp1 < val_eq_z_samp2, these are the
     * val_st_z_samp2 only.
     */

                 F2j = val_st_z_samp2;

    /* Set the line of values equal to zj to the actual line
     * of the last value picked for zj of sample 1 only in
     * this case.
     */

          val_st_z_samp1 = val_eq_z_samp1;
```

```
    /* next the line of the next value z, i.e., zj+1 is
     * addressed.  Here, only sample 1 must be addressed.
     */
                  val_eq_z_samp1++;

                  if (val_eq_z_samp2 == 0)
                          {
                          val_eq_z_samp2 = stop_loop2;
                          }
                  }
                  }

            denom_1_aux = n_total * F1j - n_sample1 * H_j;
            denom_2_aux = n_total * F2j - n_sample2 * H_j;

            sum_adk_samp1 = sum_adk_samp1 + hj
                    * (denom_1_aux * denom_1_aux) /
                                       (H_j * (n_total - H_j)
                    - n_total * hj / 4);
            sum_adk_samp2 = sum_adk_samp2 + hj
           * (denom_2_aux * denom_2_aux) /
                                (H_j * (n_total - H_j)
         - n_total * hj / 4);

            next_z_sample2 = false;
            equal_z_both_samples = false;

    /* index to count the z.  It is only required to prevent
     * the while slope to execute endless
     */
            j++;
            }

    // calculating the adk value is the final step.
    adk_result = (double) (n_total - 1) / (n_total
           * n_total * (k - 1))
            * (sum_adk_samp1 / n_sample1
            + sum_adk_samp2 / n_sample2);


    /* if(adk_result <= adk_criterium)
     * adk_2_sample test is passed
     */
    return adk_result <= adk_criterium;
 }
```

Appendix C. Glossary

ADK	Anderson-Darling K-Sample test, a test used to check whether two samples have the same statistical distribution.
ECMP	Equal Cost Multipath, a load-balancing mechanism evaluating MPLS Labels stacks, IP addresses, and ports.
EDF	The "empirical distribution function" of a set of scalar measurements is a function F(x), which for any x gives the fractional proportion of the total measurements that were smaller than or equal to x.
Metric	A measured quantity related to the performance and reliability of the Internet, expressed by a value. This could be a singleton (single value), a sample of single values, or a statistic based on a sample of singletons.
OWAMP	One-Way Active Measurement Protocol, a protocol for communication between IPPM measurement systems specified by IPPM.
OWD	One-Way Delay, a performance metric specified by IPPM.
Sample metric	A sample metric is derived from a given singleton metric by evaluating a number of distinct instances together.
Singleton metric	A singleton metric is, in a sense, one atomic measurement of this metric.
Statistical metric	A ’statistical’ metric is derived from a given sample metric by computing some statistic of the values defined by the singleton metric on the sample.
TWAMP	Two-way Active Measurement Protocol, a protocol for communication between IPPM measurement systems specified by IPPM.

Authors' Addresses

Ruediger Geib (editor)
Deutsche Telekom
Heinrich Hertz Str. 3-7
Darmstadt 64295
Germany

Phone: +49 6151 58 12747
EMail: Ruediger.Geib@telekom.de

Al Morton
AT&T Labs
200 Laurel Avenue South
Middletown, NJ 07748
USA

Phone: +1 732 420 1571
Fax: +1 732 368 1192
EMail: acmorton@att.com
URI: http://home.comcast.net/~acmacm/

Reza Fardid
Cariden Technologies
888 Villa Street, Suite 500
Mountain View, CA 94041
USA

Phone:
EMail: rfardid@cariden.com

Alexander Steinmitz
Deutsche Telekom
Memmelsdorfer Str. 209b
Bamberg 96052
Germany

Phone:
EMail: Alexander.Steinmitz@telekom.de