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Metrics and Methods for IP Capacity
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Abstract

This memo revisits the problem of Network Capacity metrics first examined in [RFC 5136](#). The memo specifies a more practical Maximum IP-layer Capacity metric definition catering for measurement purposes, and outlines the corresponding methods of measurement.

Requirements Language

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [BCP 14](#) [[RFC2119](#)] [[RFC8174](#)] when, and only when, they appear in all capitals, as shown here.

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IP Capacity Metrics/Methods

November 2019

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[1.](#) Introduction

The IETF's efforts to define Network and Bulk Transport Capacity have been chartered and progressed for over twenty years. Over that time, the performance community has seen development of Informative definitions in [[RFC3148](#)] for Framework for Bulk Transport Capacity (BTC), [RFC 5136](#) for Network Capacity and Maximum IP-layer Capacity, and the Experimental metric definitions and methods in [[RFC8337](#)], Model-Based Metrics for BTC.

This memo revisits the problem of Network Capacity metrics examined first in [[RFC3148](#)] and later in [[RFC5136](#)]. Maximum IP-Layer Capacity and [[RFC3148](#)] Bulk Transfer Capacity (goodput) are different metrics. Max IP-layer Capacity is like the theoretical goal for goodput. There are many metrics in [[RFC5136](#)], such as Available Capacity. Measurements depend on the network path under test and the use case. Here, the main use case is to assess the maximum capacity of the access network, with specific performance criteria used in the measurement.

This memo recognizes the importance of a definition of a Maximum IP-layer Capacity Metric at a time when access speeds have increased dramatically; a definition that is both practical and effective for the performance community's needs, including Internet users. The metric definition is intended to use Active Methods of Measurement [[RFC7799](#)], and a method of measurement is included.

The most direct active measurement of IP-layer Capacity would use IP packets, but in practice a transport header is needed to traverse address and port translators. UDP offers the most direct assessment

possibility, and in the [[copycat](#)][copycat] measurement study to investigate whether UDP is viable as a general Internet transport protocol, the authors found that a high percentage of paths tested support UDP transport. A number of liaisons have been exchanged on this topic [refs to ITU-T SG12, ETSI STQ, BBF liaisons], discussing the laboratory and field tests that support the UDP-based approach to IP-layer Capacity measurement.

This memo also recognizes the many updates to the IP Performance Metrics Framework [[RFC2330](#)] published over twenty years, and makes use of [[RFC7312](#)] for Advanced Stream and Sampling Framework, and [RFC 8468](#) [[RFC8468](#)] IPv4, IPv6, and IPv4-IPv6 Coexistence Updates.

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NOTE: The text contains a few Author comments, in brackets [RG: , acm:]

[2.](#) Scope and Goals

The scope of this memo is to define a metric and corresponding method to unambiguously perform Active measurements of Maximum IP-Layer Capacity, along with related metrics and methods.

The main goal is to harmonize the specified metric and method across the industry, and this memo is the vehicle through which working group (and eventually, IETF) consensus will be captured and communicated to achieve broad agreement, and possibly result in changes in the specifications of other Standards Development Organizations (SDO) (through the SDO's normal contribution process, or through liaison exchange).

A local goal is to aid efficient test procedures where possible, and to recommend reporting with additional interpretation of the results. Also, to foster the development of protocol support for this metric and method of measurement (all active testing protocols currently defined by the IPPM WG are UDP-based, meeting a key requirement of these methods).

[3.](#) Motivation

As with any problem that has been worked for many years in various SDOs without any special attempts at coordination, various solutions for metrics and methods have emerged.

There are five factors that have changed (or begun to change) in the 2013–2019 time frame, and the presence of any one of them on the path requires features in the measurement design to account for the changes:

1. Internet access is no longer the bottleneck for many users.
2. Both speed and latency are important to user's satisfaction.
3. UDP's growing role in Transport, in areas where TCP once dominated.
4. Content and applications moving physically closer to users.
5. Less emphasis on ISP gateway measurements, possibly due to less traffic crossing ISP gateways in future.

[4.](#) General Parameters and Definitions

This section lists the REQUIRED input factors to specify a Sender or Receiver metric.

- o Src, the address of a host (such as the globally routable IP address).
- o Dst, the address of a host (such as the globally routable IP address).
- o i, the limit on the number of Hops a specific packet may visit as it traverses from the host at Src to the host at Dst (such as the TTL or Hop Limit).
- o MaxHops, the maximum value of i used, (i=1,2,3,...MaxHops).
- o T0, the time at the start of measurement interval, when packets are first transmitted from the Source.
- o I, the duration of a measurement interval (default 10 sec)

- o dt, the duration of N equal sub-intervals in I (default 1 sec)
- o Tmax, a maximum waiting time for test packets to arrive at the destination, set sufficiently long to disambiguate packets with long delays from packets that are discarded (lost), such that the distribution of one-way delay is not truncated.
- o F, the number of different flows synthesized by the method (default 1 flow)
- o flow, the stream of packets with the same n-tuple of designated header fields that (when held constant) result in identical treatment in a multi-path decision (such as the decision taken in load balancing). Note: The IPv6 flow label MAY be included in the flow definition when routers have complied with [\[RFC6438\]](#) guidelines at the Tunnel End Points (TEP), and the source of the measurement is a TEP.
- o Type-P, the complete description of the packets for which this assessment applies (including the flow-defining fields). Note that the UDP transport layer is one requirement specified below. Type-P is a parallel concept to "population of interest" defined in ITU-T Rec. Y.1540.
- o PM, a list of fundamental metrics, such as loss, delay, and reordering, and corresponding Target performance threshold. At

least one fundamental metric and Target performance threshold MUST be supplied (such as One-way IP Packet Loss [\[RFC7680\]](#) equal to zero).

A non-Parameter which is required for several metrics is defined below:

- o T, the host time of the *first* test packet's *arrival* as measured at MP(Dst). There may be other packets sent between source and destination hosts that are excluded, so this is the time of arrival of the first packet used for measurement of the metric.

Note that time stamps, sequence numbers, etc. will be established by the test protocol.

[5.](#) IP-Layer Capacity Singleton Metric Definitions

This section sets requirements for the following components to support the Maximum IP-layer Capacity Metric.

[5.1.](#) Formal Name

Type-P-IP-Capacity, or informally called IP-layer Capacity.

Note that Type-P depends on the chosen method.

[5.2.](#) Parameters

This section lists the REQUIRED input factors to specify the metric, beyond those listed in [Section 4](#).

No additional Parameters are needed.

[5.3.](#) Metric Definitions

This section defines the REQUIRED aspects of the measureable IP-layer Capacity metric (unless otherwise indicated) for measurements between specified Source and Destination hosts:

Define the IP-layer capacity, $C(T,I,PM)$, to be the number of IP-layer bits (including header and data fields) in packets that can be transmitted from the Src host and correctly received by the Dst host during one contiguous sub-interval, dt .

The number of these IP-layer bits is designated $n_0[dt_n-1,dt_n]$ for a specific dt_n .

When the packet size is known and of fixed size, the packet count during a single sub-interval dt multiplied by the total bits in IP header and data fields is equal to $n_0[dt_n-1,dt_n]$.

Anticipating a Sample of Singletons, the interval dt SHOULD be set to a natural number m so that $T+I = T + m \times dt$ with $dt_n - dt_{n-1} = dt$ and with $0 < n \leq m$.

Parameter PM represents other performance metrics [see section Related Round-Trip Delay and Loss Definitions below]; their measurement results SHALL be collected during measurement of IP-layer Capacity and associated with the corresponding dtn for further evaluation and reporting.

Mathematically, this definition can be represented as:

$$C(T,I,PM) = \frac{(n0[dt_n-1,dt_n])}{dt}$$

Equation for IP-Layer Capacity

and:

- o n0 is the total number of IP-layer header and payload bits that can be transmitted in Standard Formed packets from the Src host and correctly received by the Dst host during one contiguous sub-interval, dt in length, during the interval [T, T+I],
- o C(T,I,PM) the IP-Layer Capacity, corresponds to the value of n0 measured in any sub-interval ending at dtn (meaning T + n*dt), divided by the length of sub-interval, dt.
- o all sub-intervals SHOULD be of equal duration. Choosing dt as non-overlapping consecutive time intervals allows for a simple implementation.
- o The bit rate of the physical interface of the measurement device must be higher than that of the link whose C(T,I,PM) is to be measured.

Measurements according to these definitions SHALL use UDP transport layer.

RTD[*dtn*-1,*dtn*] is defined as a sample of the [[RFC2681](#)] Round-trip Delay between the Src host and the Dst host over the interval [*T*,*T*+*I*]. The statistics used to to summarize RTD[*dtn*-1,*dtn*] MAY include the minimum, maximum, and mean.

RTL[*dtn*-1,*dtn*] is defined as a sample of the [[RFC6673](#)] Round-trip Loss between the Src host and the Dst host over the interval [*T*,*T*+*I*]. The statistics used to to summarize RTL[*dtn*-1,*dtn*] MAY include the lost packet count and the lost packet ratio.

[5.5.](#) Discussion

See the corresponding section for Maximum IP-Layer Capacity.

[5.6.](#) Reporting the Metric

The IP-Layer Capacity SHALL be reported with meaningful resolution, in units of Megabits per second (Mbps).

The Related Round Trip Delay and/or Loss metric measurements for the same Singleton SHALL be reported, also with meaningful resolution for the values measured.

Individual Capacity measurements MAY be reported in a manner consistent with the Maximum IP-Layer Capacity, see [Section 9](#).

[6.](#) Maximum IP-Layer Capacity Metric Definitions (Statistic)

This section sets requirements for the following components to support the Maximum IP-layer Capacity Metric.

[6.1.](#) Formal Name

Type-P-Max-IP-Capacity, or informally called Maximum IP-layer Capacity.

Note that Type-P depends on the chosen method.

[6.2.](#) Parameters

This section lists the REQUIRED input factors to specify the metric, beyond those listed in [Section 4](#).

No additional Parameters or definitions are needed.

6.3. Metric Definitions

This section defines the REQUIRED aspects of the Maximum IP-layer Capacity metric (unless otherwise indicated) for measurements between specified Source and Destination hosts:

Define the Maximum IP-layer capacity, $\text{Maximum_C}(T,I,PM)$, to be the maximum number of IP-layer bits $n0[dt_n-1,dt_n]$ that can be transmitted in packets from the Src host and correctly received by the Dst host, over all dt length intervals in $[T, T+I]$, and meeting the PM criteria. Equivalently the Maximum of a Sample of size m of $C(T,I,PM)$ collected during the interval $[T, T+I]$ and meeting the PM criteria.

The interval dt SHOULD be set to a natural number m so that $T+I = T + m*dt$ with $dt_n - dt_{n-1} = dt$ and with $0 < n \leq m$.

Parameter PM represents the other performance metrics [see section Related Round-Trip Delay and Loss Definitions below] and their measurement results for the maximum IP-layer capacity. At least one target performance threshold (PM criterion) MUST be defined. If more than one target performance threshold is defined, then the sub-interval with maximum number of bits transmitted MUST meet all the target performance thresholds.

Mathematically, this definition can be represented as:

$$\text{Maximum_C}(T,I,PM) = \frac{\max_{[T,T+I]} (n0[dt_n-1,dt_n])}{dt}$$

where:

$T \qquad \qquad \qquad T+I$

|

|

|

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|

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|

|

|

|

|

$dt_n=0$
1
2
3
4
5
6
7
8
9
 $m=10$

Equation for Maximum Capacity

and:

- o $n0$ is the total number of IP-layer header and payload bits that can be transmitted in Standard Formed packets from the Src host and correctly received by the Dst host during one contiguous sub-

interval, dt in length, during the interval $[T, T+I]$,

- o Maximum $_C(T,I,PM)$ the Maximum IP-Layer Capacity, corresponds to the maximum value of n_0 measured in any sub-interval ending at dtn (meaning $T + n*dt$), divided by the constant length of all sub-intervals, dt .
- o all sub-intervals SHOULD be of equal duration. Choosing dt as non-overlapping consecutive time intervals allows for a simple implementation.
- o The bit rate of the physical interface of the measurement systems must be higher than that of the link whose Maximum $_C(T,I,PM)$ is to be measured (the bottleneck link).

In this definition, the m sub-intervals can be viewed as trials when the Src host varies the transmitted packet rate, searching for the maximum n_0 that meets the PM criteria measured at the Dst host in a test of duration, I . When the transmitted packet rate is held constant at the Src host, the m sub-intervals may also be viewed as trials to evaluate the stability of n_0 and metric(s) in the PM list over all dt -length intervals in I .

Measurements according to these definitions SHALL use UDP transport layer.

[6.4.](#) Related Round-Trip Delay and Loss Definitions

RTD[$dtn-1,dtn$] is defined as a sample of the [\[RFC2681\]](#) Round-trip Delay between the Src host and the Dst host over the interval $[T,T+I]$, and corresponds to the dt interval containing Maximum $_C(T,I,PM)$. The statistics used to to summarize RTD[$dtn-1,dtn$] MAY include the minimum, maximum, and mean.

RTL[$dtn-1,dtn$] is defined as a sample of the [\[RFC6673\]](#) Round-trip Loss between the Src host and the Dst host over the interval $[T,T+I]$ and corresponds to the dt interval containing Maximum $_C(T,I,PM)$. The statistics used to to summarize RTL[$dtn-1,dtn$] MAY include the lost packet count and the lost packet ratio.

[6.5.](#) Discussion

If traffic conditioning applies along a path for which $\text{Maximum_C}(T, I, PM)$ is to be determined, different values for dt SHOULD be picked and measurements be executed during multiple intervals $[T, T+I]$. Any single interval dt SHOULD be chosen so that is an integer multiple of increasing values k times serialisation delay of a path MTU at the physical interface speed where traffic conditioning is expected. This should avoid taking configured burst tolerance singletons as a valid $\text{Maximum_C}(T, I, PM)$ result.

A $\text{Maximum_C}(T, I, PM)$ without any indication of bottleneck congestion, be that an increasing latency, packet loss or ECN marks during a measurement interval I , is likely to underestimate $\text{Maximum_C}(T, I, PM)$.

[6.6.](#) Reporting the Metric

The Maximum IP-Layer Capacity SHALL be reported with meaningful resolution, in units of Megabits per second.

The Related Round Trip Delay and/or Loss metric measurements for the same Singleton SHALL be reported, also with meaningful resolution for the values measured.

When there are demonstrated and repeatable modes in the Sample, then the Maximum IP-Layer Capacity SHALL be reported for each mode, along with the relative time from the beginning of the stream that the mode was observed to be present. Bimodal Maxima have been observed with some services, sometimes called a "turbo" mode" intending to deliver short transfers more quickly, or reduce the initial buffering time for some video streams.

[7.](#) IP-Layer Sender Bit Rate Singleton Metric Definitions

This section sets requirements for the following components to support the IP-layer Sender Bitrate Metric.

[7.1.](#) Formal Name

Type-P-IP-Sender-Bit-Rate, or informally called IP-layer Sender Bitrate.

Note that Type-P depends on the chosen method.

[7.2.](#) Parameters

This section lists the REQUIRED input factors to specify the metric, beyond those listed in [Section 4](#).

- o S, the duration of the measurement interval at the Source
- o st, the nominal duration of N sub-intervals in S (default = 0.05 seconds)

S SHALL be longer than I, primarily to account for on-demand activation of the path, or any preamble to testing required.

st SHOULD be much smaller than the sub-interval dt. The st parameter does not have relevance when the Source is transmitting at a fixed rate throughout S.

[7.3.](#) Metric Definition

This section defines the REQUIRED aspects of the IP-layer Sender Bitrate metric (unless otherwise indicated) for measurements at the specified Source on packets addressed for the intended Destination host and matching the required Type-P:

Define the IP-layer Sender Bit Rate, $B(S, st)$, to be the number of IP-layer bits (including header and data fields) that are transmitted from the Source during one contiguous sub-interval, st, during the test interval S (where S SHALL be longer than I), and where the fixed-size packet count during that single sub-interval st also provides the number of IP-layer bits in any interval: $n0[stn-1, stn]$.

Measurements according to these definitions SHALL use UDP transport layer. Any feedback from Dst host to Src host received by Src host during an interval $[stn-1, stn]$ MUST NOT result in an adaptation of the Src host traffic conditioning during this interval.

[7.4.](#) Discussion

Both the Sender and Receiver or (source and destination) bit rates SHOULD be assessed as part of a measurement.

[7.5.](#) Reporting the Metric

The IP-Layer Sender Bit Rate SHALL be reported with meaningful resolution, in units of Megabits per second.

Individual IP-Layer Sender Bit Rate measurements are discussed further in [Section 9](#).

[8.](#) Method of Measurement

The duration of a test, I, MUST be constrained in a production network, since this is an active test method and it will likely cause congestion on the Src to Dst host path during a test.

Additional Test methods and configurations may be provided in this section, after review and further testing.

[8.1.](#) Load Rate Adjustment Algorithm (from udpst)

A table is pre-built defining all the offered load rates that will be supported ($R_1 - R_n$, in ascending order). Each rate is defined as datagrams of size S , sent as a burst of count C , every time interval T . While it is advantageous to use datagrams of as large a size as possible, it may be prudent to use a slightly smaller maximum that allows for secondary protocol headers and/or tunneling without resulting in IP-layer fragmentation.

At the beginning of a test, the sender begins sending at rate R_1 and the receiver starts a feedback timer at interval F (while awaiting inbound datagrams). As datagrams are received they are checked for sequence number anomalies (loss, out-of-order, duplication, etc.) and the delay variation is measured (one-way or round-trip). This information is accumulated until the feedback timer F expires and a status feedback message is sent from the receiver back to the sender, to communicate this information. The accumulated statistics are then

reset by the receiver for the next feedback interval. As feedback messages are received back at the sender, they are evaluated to determine how to adjust the current offered load rate (R_x).

If the feedback indicates that there were no sequence number anomalies AND the delay variation was below the lower threshold, the offered load rate is increased. If congestion has not been confirmed up to this point, the offered load rate is increased by more than one rate (e.g., R_x+10). This allows the offered load to quickly reach a near-maximum rate. Conversely, if congestion has been previously confirmed, the offered load rate is only increased by one (R_x+1).

If the feedback indicates that sequence number anomalies were detected OR the delay variation was above the upper threshold, the offered load rate is decreased. If congestion is confirmed by the current feedback message being processed, the offered load rate is decreased by more than one rate (e.g., R_x-30). This one-time reduction is intended to compensate for the fast initial ramp-up. In all other cases, the offered load rate is only decreased by one (R_x-1).

If the feedback indicates that there were no sequence number anomalies AND the delay variation was above the lower threshold, but below the upper threshold, the offered load rate is not changed. This allows time for recent changes in the offered load rate to stabilize, and the feedback to represent current conditions more accurately.

Lastly, the method for confirming congestion is that there were sequence number anomalies OR the delay variation was above the upper threshold for two consecutive feedback intervals.

[8.2.](#) Measurement Qualification or Verification

When assessing a Maximum rate as the metric specifies, artificially high (optimistic) values might be measured until some buffer on the path is filled. Other causes include bursts of back-to-back packets with idle intervals delivered by a path, while the measurement interval (dt) is small and aligned with the bursts. The artificial

values might result in an un-sustainable Maximum Capacity observed when the method of measurement is searching for the Maximum, and that would not do. This situation is different from the bi-modal service rates (discussed under Reporting), which are characterized by a multi-second duration (much longer than the measured RTT) and repeatable behavior.

There are many ways that the Method of Measurement could handle this false-max issue. The default value for measurement of singletons (dt = 1 second) has proven to be of practical value during tests of this method, allows the bimodal service rates to be characterized, and it has an obvious alignment with the reporting units (Mbps).

Another approach comes from [Section 24 of RFC 2544](#)[\[RFC2544\]](#) and its discussion of Trial duration, where relatively short trials conducted as part of the search are followed by longer trials to make the final determination. In the production network, measurements of singletons and samples (the terms for trials and tests of Lab Benchmarking) must be limited in duration because they may be service-affecting. But there is sufficient value in repeating a sample with a fixed sending rate determined by the previous search for the Max IP-layer Capacity, to qualify the result in terms of the other performance metrics measured at the same time.

A qualification measurement for the search result is a subsequent measurement, sending at a fixed 99.x % of the Max IP-layer Capacity for I, or an indefinite period. The same Max Capacity Metric is applied, and the Qualification for the result is a sample without packet loss or a growing minimum delay trend in subsequent singletons (or each dt of the measurement interval, I). Samples exhibiting losses or increasing queue occupation require a repeated search and/or test at reduced fixed sender rate for qualification.

Here, as with any Active Capacity test, the test duration must be kept short. 10 second tests for each direction of transmission are common today. The default measurement interval specified here is I = 10 seconds). In combination with a fast search method and user-

network coordination, the concerns raised in [RFC 6815](#)[\[RFC6815\]](#) are alleviated. The method for assessing Max IP Capacity is different from classic [\[RFC2544\]](#) methods: they use short term load adjustment and are sensitive to loss and delay, like other congestion control

algorithms used on the Internet every day.

8.3. Measurement Considerations

In general, the wide-spread measurements that this memo encourages will encounter wide-spread behaviors. The bimodal IP Capacity behavior is a good example.

The path measured may be state-full based on many factors, and the Parameter "Time of day" when a test starts may not be enough enough information. Repeatable testing may require the time from the beginning of a measured flow, and how the flow is constructed including how much traffic has already been sent on that flow when a state-change is observed, because the state-change may be based on time or bytes sent or both.

Many different traffic shapers and on-demand access technology may be encountered, as anticipated in [[RFC7312](#)], and play a key role in measurement results. Methods MUST be prepared to provide a short preamble transmission to activate on-demand access, and to discard the preamble from subsequent test results.

In general, results depend on the sending stream characteristics; the measurement community has known this for a long time, and to keep it front of mind. Although the default is a single flow (F=1) for testing, use of multiple flows may be advantageous for the following reasons:

1. the test hosts may be able to create higher load than with a single flow, or parallel test hosts may be used to generate 1 flow each.
2. there may be link aggregation present (flow-based load balancing) and multiple flows are need to occupy each member of the aggregate.

Each flow would be controlled using its own implementation of the Load Adjustment (Search) Algorithm.

As testing continues, implementers should expect some evolution in the methods.

9. Reporting

The Maximum IP-Layer Capacity results SHOULD be reported in the format of a table with a row for each of the test Phases and Number of Flows. There SHOULD be columns for the phases with number of flows, and for the resultant Maximum IP-Layer Capacity results for the aggregate and each flow tested.

The PM list metrics corresponding to the sub-interval where the Maximum Capacity occurred MUST accompany a report of Maximum IP-Layer Capacity results, for each test phase.

Phase, # Flows	Max IP-Layer Capacity, Mbps	Loss Ratio	RTT min, max, msec
Search,1	967.31	0.0002	30, 58
Verify,1	966.00	0.0000	30, 38

Maximum IP-layer Capacity Results

Static and configuration parameters:

The sub-interval time, dt, MUST accompany a report of Maximum IP-Layer Capacity results, and the remaining Parameters from [Section 4](#), General Parameters.

The IP-Layer Sender Bit rate results SHOULD be reported in the format of a table with a row for each of the test Phases, sub-intervals (st) and Number of Flows. There SHOULD be columns for the phases with number of flows, and for the resultant IP-Layer Sender Bit rate results for the aggregate and each flow tested.

Phase, Flow or Aggregate	st, sec	Sender Bit Rate, Mbps	??
Search,1	0.00 - 0.05	345	--
Search,2	0.00 - 0.05	289	--
Search,Agg	0.00 - 0.05	634	--

IP-layer Sender Bit Rate Results

Static and configuration parameters:

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The subinterval time, st, MUST accompany a report of Sender IP-Layer Bit Rate results.

Also, the values of the remaining Parameters from [Section 4](#), General Parameters, MUST be reported.

[10.](#) Security Considerations

Active metrics and measurements have a long history of security considerations [add references to LMAP Framework, etc.].

<There are certainly some new ones for Capacity testing>

[11.](#) IANA Considerations

This memo makes no requests of IANA.

[12.](#) Acknowledgements

Thanks to Joachim Fabini, Matt Mathis, and Ignacio Alvarez-Hamelin for their extensive comments on the memo and related topics.

[13.](#) References

[13.1.](#) Normative References

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