

IP Performance Working Group
Internet-Draft
Intended status: Experimental
Expires: March 19, 2018

M. Mathis
Google, Inc
A. Morton
AT&T Labs
September 15, 2017

Model Based Metrics for Bulk Transport Capacity
draft-ietf-ippm-model-based-metrics-13.txt

Abstract

We introduce a new class of Model Based Metrics designed to assess if a complete Internet path can be expected to meet a predefined Target Transport Performance by applying a suite of IP diagnostic tests to successive subpaths. The subpath-at-a-time tests can be robustly applied to critical infrastructure, such as network interconnections or even individual devices, to accurately detect if any part of the infrastructure will prevent paths traversing it from meeting the Target Transport Performance.

Model Based Metrics rely on mathematical models to specify a Targeted Suite of IP Diagnostic tests, designed to assess whether common transport protocols can be expected to meet a predetermined Target Transport Performance over an Internet path.

For Bulk Transport Capacity the IP diagnostics are built using test streams and statistical criteria for evaluating the packet transfer that mimic TCP over the complete path. The temporal structure of the test stream (bursts, etc) mimic TCP or other transport protocol carrying bulk data over a long path. However they are constructed to be independent of the details of the subpath under test, end systems or applications. Likewise the success criteria evaluates the packet transfer statistics of the subpath against criteria determined by protocol performance models applied to the Target Transport Performance of the complete path. The success criteria also does not depend on the details of the subpath, end systems or application.

Status of This Memo

This Internet-Draft is submitted in full conformance with the provisions of BCP 78 and BCP 79.

Internet-Drafts are working documents of the Internet Engineering Task Force (IETF). Note that other groups may also distribute working documents as Internet-Drafts. The list of current Internet-Drafts is at <http://datatracker.ietf.org/drafts/current/>.

Internet-Drafts are draft documents valid for a maximum of six months and may be updated, replaced, or obsoleted by other documents at any time. It is inappropriate to use Internet-Drafts as reference material or to cite them other than as "work in progress."

This Internet-Draft will expire on March 19, 2018.

Copyright Notice

Copyright (c) 2017 IETF Trust and the persons identified as the document authors. All rights reserved.

This document is subject to BCP 78 and the IETF Trust's Legal Provisions Relating to IETF Documents (<http://trustee.ietf.org/license-info>) in effect on the date of publication of this document. Please review these documents carefully, as they describe your rights and restrictions with respect to this document. Code Components extracted from this document must include Simplified BSD License text as described in Section 4.e of the Trust Legal Provisions and are provided without warranty as described in the Simplified BSD License.

Table of Contents

1. Introduction	3
1.1. Version Control	5
2. Overview	8
3. Terminology	10
4. Background	17
4.1. TCP properties	18
4.2. Diagnostic Approach	20
4.3. New requirements relative to RFC 2330	21
5. Common Models and Parameters	22
5.1. Target End-to-end parameters	22
5.2. Common Model Calculations	23
5.3. Parameter Derating	24
5.4. Test Preconditions	24
6. Generating test streams	25
6.1. Mimicking slowstart	26
6.2. Constant window pseudo CBR	27
6.3. Scanned window pseudo CBR	28
6.4. Concurrent or channelized testing	29
7. Interpreting the Results	30
7.1. Test outcomes	30
7.2. Statistical criteria for estimating run_length	31
7.3. Reordering Tolerance	34
8. IP Diagnostic Tests	34
8.1. Basic Data Rate and Packet Transfer Tests	35

8.1.1.	Delivery Statistics at Paced Full Data Rate	35
8.1.2.	Delivery Statistics at Full Data Windowed Rate	35
8.1.3.	Background Packet Transfer Statistics Tests	35
8.2.	Standing Queue Tests	36
8.2.1.	Congestion Avoidance	37
8.2.2.	Bufferbloat	37
8.2.3.	Non excessive loss	38
8.2.4.	Duplex Self Interference	38
8.3.	Slowstart tests	39
8.3.1.	Full Window slowstart test	39
8.3.2.	Slowstart AQM test	39
8.4.	Sender Rate Burst tests	40
8.5.	Combined and Implicit Tests	41
8.5.1.	Sustained Bursts Test	41
8.5.2.	Passive Measurements	42
9.	An Example	43
9.1.	Observations about applicability	44
10.	Validation	44
11.	Security Considerations	46
12.	Acknowledgments	46
13.	IANA Considerations	47
14.	Informative References	47
Appendix A.	Model Derivations	51
A.1.	Queueless Reno	51
Appendix B.	The effects of ACK scheduling	52
Appendix C.	Version Control	53
Authors' Addresses	53

1. Introduction

Model Based Metrics (MBM) rely on peer-reviewed mathematical models to specify a Targeted Suite of IP Diagnostic tests, designed to assess whether common transport protocols can be expected to meet a predetermined Target Transport Performance over an Internet path. This note describes the modeling framework to derive the test parameters for assessing an Internet path's ability to support a predetermined Bulk Transport Capacity.

Each test in the Targeted IP Diagnostic Suite (TIDS) measures some aspect of IP packet transfer needed to meet the Target Transport Performance. For Bulk Transport Capacity the TIDS includes IP diagnostic tests to verify that there is: sufficient IP capacity (data rate); sufficient queue space at bottlenecks to absorb and deliver typical transport bursts; and that the background packet loss ratio is low enough not to interfere with congestion control; and other properties described below. Unlike typical IPPM metrics which yield measures of network properties, Model Based Metrics nominally yield pass/fail evaluations of the ability of standard transport

protocols to meet the specific performance objective over some network path.

In most cases, the IP diagnostic tests can be implemented by combining existing IPPM metrics with additional controls for generating test streams having a specified temporal structure (bursts or standing queues caused by constant bit rate streams, etc.) and statistical criteria for evaluating packet transfer. The temporal structure of the test streams mimic transport protocol behavior over the complete path; the statistical criteria models the transport protocol's response to less than ideal IP packet transfer. In control theory terms, the tests are "open loop". Note that running a test requires the coordinated activity of sending and receiving measurement points.

This note addresses Bulk Transport Capacity. It describes an alternative to the approach presented in "A Framework for Defining Empirical Bulk Transfer Capacity Metrics" [RFC3148]. Other Model Based Metrics may cover other applications and transports, such as VoIP over UDP and RTP, and new transport protocols.

This note assumes a traditional Reno TCP style self clocked, window controlled transport protocol that uses packet loss and ECN CE marks for congestion feedback. There are currently some experimental protocols and congestion control algorithms that are rate based or otherwise fall outside of these assumptions. In the future these new protocols and algorithms may call for revised models.

The MBM approach, mapping Target Transport Performance to a Targeted IP Diagnostic Suite (TIDS) of IP tests, solves some intrinsic problems with using TCP or other throughput maximizing protocols for measurement. In particular all throughput maximizing protocols (and TCP congestion control in particular) cause some level of congestion in order to detect when they have reached the available capacity limitation of the network. This self inflicted congestion obscures the network properties of interest and introduces non-linear dynamic equilibrium behaviors that make any resulting measurements useless as metrics because they have no predictive value for conditions or paths different than that of the measurement itself. In order to prevent these effects it is necessary to avoid the effects of TCP congestion control in the measurement method. These issues are discussed at length in Section 4. Readers whom are unfamiliar with basic properties of TCP and TCP-like congestion control may find it easier to start at Section 4 or Section 4.1.

A Targeted IP Diagnostic Suite does not have such difficulties. IP diagnostics can be constructed such that they make strong statistical statements about path properties that are independent of the

measurement details, such as vantage and choice of measurement points.

1.1. Version Control

RFC Editor: Please remove this entire subsection prior to publication.

REF Editor: The reference to draft-ietf-tcpm-rack is to attribute an idea. This document should not block waiting for the completion of that one.

Please send comments about this draft to ippm@ietf.org. See <http://goo.gl/02tkD> for more information including: interim drafts, an up to date todo list and information on contributing.

Formatted: Fri Sep 15 15:07:50 PDT 2017

Changes since -11 draft:

- o (From IESG review comments.)
- o Ben Campbell: Shorten the Abstract.
- o Mirja Kuhlewind: Reduced redundancy. (See message)
- o MK: Mention open loop in the introduction.
- o MK: Spelled out ECN and reference RFC3168.
- o MK: Added a paragraph to the introduction about assuming a traditional self clocked, window controlled transport protocol.
- o MK: Added language about initial window to the list at about bursts at the end of section 4.1.
- o MK: Network power is defined in the terminology section.
- o MK: The introduction mention coordinated activity of both endpoints.
- o MK: The security section restates that some of the tests are not intended for frequent monitoring tests as the high load can impact other traffic negatively.
- o MK: Restored "Informative References" section name.
- o And a few minor nits.

Changes since -10 draft:

- o A few more nits from various sources.
- o (From IETF LC review comments.)
- o David Mandelberg: design metrics to prevent DDOS.
- o From Robert Sparks:
 - * Remove all legacy 2119 language.
 - * Fixed Xr notation inconsistency.
 - * Adjusted abstract: tests are only partially specified.

- * Avoid rather than suppress the effects of congestion control
- * Removed the unnecessary, excessively abstract and unclear thought about IP vs TCP measurements.
- * Changed "thwarted" to "not fulfilled".
- * Qualified language about burst models.
- * Replaced "infinitesimal" with other language.
- * Added citations for the reordering strawman.
- * Pointed out that pseudo CBR tests depend on self clock.
- * Fixed some run on sentences.
- o Update language to reflect RFC7567, AQM recommendations.
- o Suggestion from Merry Mou (MIT)

Changes since -09 draft:

- o Five last minute editing nits.

Changes since -08 draft:

- o Language, spelling and usage nits.
- o Expanded the abstract describe the models.
- o Remove superfluous standards like language
- o Remove superfluous "future technology" language.
- o Interconnects -> network interconnections.
- o Added more labels to Figure 1.
- o Defined Bulk Transport.
- o Clarified "implied bottleneck IP capacity"
- o Clarified the history of the BTC metrics.
- o Clarified stochastic vs non-stochastic test traffic generation.
- o Reworked Fig 2 and 6.1 "Mimicking slowstart"
- o Described the unsynchronized parallel stream failure case.
- o Discussed how to measure devices that use virtual queues.
- o Changed section 8.5.2 (Streaming Media) to be Passive Measurements.

Changes since -07 draft:

- o Sharpened the use of "statistical criteria"
- o Sharpened the definition of test_window, and removed related redundant text in several places
- o Clarified "equilibrium" as "dynamic equilibrium, similar to processes observed in chemistry"
- o Properly explained "Heisenberg" as "observer effect"
- o Added the observation from RFC 6576 that HW and SW congestion control implementations do not generally give the same results.
- o Noted that IP and application metrics differ as to how overhead is handled. MBM is explicit about how it handles overhead.
- o Clarified the language and added a new reference about the problems caused by token bucket policers.

- o Added an subsection in the example that comments on some of issues that need to be mentioned in a future usage or applicability doc.
- o Updated ippm-2680-bis to RFC7680
- o Many terminology, punctuation and spelling nits.

Changes since -06 draft:

- o More language nits:
 - * "Targeted IP Diagnostic Suite (TIDS)" replaces "Targeted Diagnostic Suite (TDS)".
 - * "implied bottleneck IP capacity" replaces "implied bottleneck IP rate".
 - * Updated to ECN CE Marks.
 - * Added "specified temporal structure"
 - * "test stream" replaces "test traffic"
 - * "packet transfer" replaces "packet delivery"
 - * Reworked discussion of slowstart, bursts and pacing.
 - * RFC 7567 replaces RFC 2309.

Changes since -05 draft:

- o Wordsmithing on sections overhauled in -05 draft.
- o Reorganized the document:
 - * Relocated subsection "Preconditions".
 - * Relocated subsection "New Requirements relative to RFC 2330".
- o Addressed nits and not so nits by Ruediger Geib. (Thanks!)
- o Substantially tightened the entire definitions section.
- o Many terminology changes, to better conform to other docs :
 - * IP rate and IP capacity (following RFC 5136) replaces various forms of link data rate.
 - * subpath replaces link.
 - * target_window_size replaces target_pipe_size.
 - * implied bottleneck IP rate replaces effective bottleneck link rate.
 - * Packet delivery statistics replaces delivery statistics.

Changes since -04 draft:

- o The introduction was heavily overhauled: split into a separate introduction and overview.
- o The new shorter introduction:
 - * Is a problem statement;
 - * This document provides a framework;
 - * That it replaces TCP measurement by IP tests;

- * That the results are pass/fail.
- o Added a diagram of the framework to the overview
- o and introduces all of the elements of the framework.
- o Renumbered sections, reducing the depth of some section numbers.
- o Updated definitions to better agree with other documents:
- * Reordered section 2
- * Bulk [data] performance -> Bulk Transport Capacity, everywhere including the title.
- * loss rate and loss probability -> packet loss ratio
- * end-to-end path -> complete path
- * [end-to-end][target] performance -> Target Transport Performance
- * load test -> capacity test

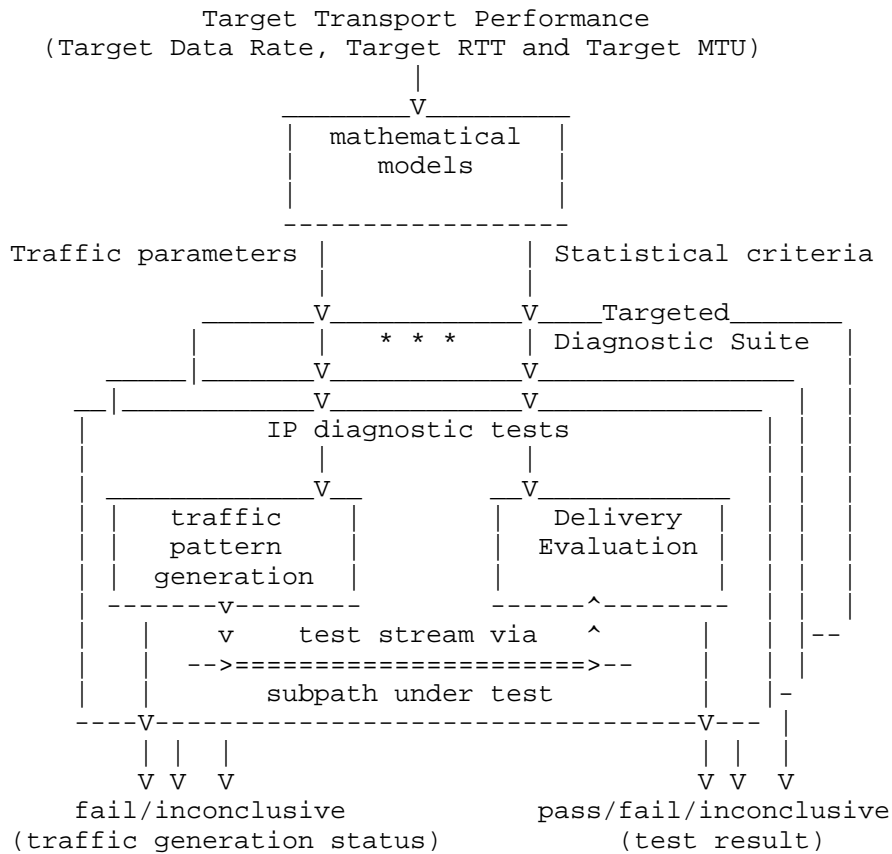
2. Overview

This document describes a modeling framework for deriving a Targeted IP Diagnostic Suite from a predetermined Target Transport Performance. It is not a complete specification, and relies on other standards documents to define important details such as packet Type-P selection, sampling techniques, vantage selection, etc. We imagine Fully Specified - Targeted IP Diagnostic Suites (FS-TIDS), that define all of these details. We use Targeted IP Diagnostic Suite (TIDS) to refer to the subset of such a specification that is in scope for this document. This terminology is defined in Section 3.

Section 4 describes some key aspects of TCP behavior and what they imply about the requirements for IP packet transfer. Most of the IP diagnostic tests needed to confirm that the path meets these properties can be built on existing IPPM metrics, with the addition of statistical criteria for evaluating packet transfer and in a few cases, new mechanisms to implement the required temporal structure. (One group of tests, the standing queue tests described in Section 8.2, don't correspond to existing IPPM metrics, but suitable new IPPM metrics can be patterned after the existing definitions.)

Figure 1 shows the MBM modeling and measurement framework. The Target Transport Performance, at the top of the figure, is determined by the needs of the user or application, outside the scope of this document. For Bulk Transport Capacity, the main performance parameter of interest is the Target Data Rate. However, since TCP's ability to compensate for less than ideal network conditions is fundamentally affected by the Round Trip Time (RTT) and the Maximum Transmission Unit (MTU) of the complete path, these parameters must also be specified in advance based on knowledge about the intended application setting. They may reflect a specific application over a real path through the Internet or an idealized application and

hypothetical path representing a typical user community. Section 5 describes the common parameters and models derived from the Target Transport Performance.



Overall Modeling Framework

Figure 1

Mathematical TCP models are used to determine Traffic parameters and subsequently to design traffic patterns that mimic TCP or other transport protocol delivering bulk data and operating at the Target Data Rate, MTU and RTT over a full range of conditions, including flows that are bursty at multiple time scales. The traffic patterns are generated based on the three Target parameters of complete path and independent of the properties of individual subpaths using the techniques described in Section 6. As much as possible the test streams are generated deterministically (precomputed) to minimize the extent to which test methodology, measurement points, measurement

vantage or path partitioning affect the details of the measurement traffic.

Section 7 describes packet transfer statistics and methods to test them against the statistical criteria provided by the mathematical models. Since the statistical criteria typically apply to the complete path (a composition of subpaths) [RFC6049], in situ testing requires that the end-to-end statistical criteria be apportioned as separate criteria for each subpath. Subpaths that are expected to be bottlenecks would then be permitted to contribute a larger fraction of the end-to-end packet loss budget. In compensation, subpaths that are not expected to exhibit bottlenecks must be constrained to contribute less packet loss. Thus the statistical criteria for each subpath in each test of a TIDS is an apportioned share of the end-to-end statistical criteria for the complete path which was determined by the mathematical model.

Section 8 describes the suite of individual tests needed to verify all of required IP delivery properties. A subpath passes if and only if all of the individual IP diagnostic tests pass. Any subpath that fails any test indicates that some users are likely to fail to attain their Target Transport Performance under some conditions. In addition to passing or failing, a test can be deemed to be inconclusive for a number of reasons including: the precomputed traffic pattern was not accurately generated; the measurement results were not statistically significant; and others such as failing to meet some required test preconditions. If all tests pass but some are inconclusive, then the entire suite is deemed to be inconclusive.

In Section 9 we present an example TIDS that might be representative of High Definition (HD) video, and illustrate how Model Based Metrics can be used to address difficult measurement situations, such as confirming that inter-carrier exchanges have sufficient performance and capacity to deliver HD video between ISPs.

Since there is some uncertainty in the modeling process, Section 10 describes a validation procedure to diagnose and minimize false positive and false negative results.

3. Terminology

Terms containing underscores (rather than spaces) appear in equations and typically have algorithmic definitions.

General Terminology:

Target: A general term for any parameter specified by or derived from the user's application or transport performance requirements.

Target Transport Performance: Application or transport performance target values for the complete path. For Bulk Transport Capacity defined in this note the Target Transport Performance includes the Target Data Rate, Target RTT and Target MTU as described below.

Target Data Rate: The specified application data rate required for an application's proper operation. Conventional Bulk Transport Capacity (BTC) metrics are focused on the Target Data Rate, however these metrics had little or no predictive value because they do not consider the effects of the other two parameters of the Target Transport Performance, the RTT and MTU of the complete paths.

Target RTT (Round Trip Time): The specified baseline (minimum) RTT of the longest complete path over which the user expects to be able to meet the target performance. TCP and other transport protocol's ability to compensate for path problems is generally proportional to the number of round trips per second. The Target RTT determines both key parameters of the traffic patterns (e.g. burst sizes) and the thresholds on acceptable IP packet transfer statistics. The Target RTT must be specified considering appropriate packets sizes: MTU sized packets on the forward path, ACK sized packets (typically header_overhead) on the return path. Note that Target RTT is specified and not measured, MBM measurements derived for a given target_RTT will be applicable to any path with a smaller RTTs.

Target MTU (Maximum Transmission Unit): The specified maximum MTU supported by the complete path the over which the application expects to meet the target performance. In this document assume a 1500 Byte MTU unless otherwise specified. If some subpath has a smaller MTU, then it becomes the Target MTU for the complete path, and all model calculations and subpath tests must use the same smaller MTU.

Targeted IP Diagnostic Suite (TIDS): A set of IP diagnostic tests designed to determine if an otherwise ideal complete path containing the subpath under test can sustain flows at a specific target_data_rate using target_MTU sized packets when the RTT of the complete path is target_RTT.

Fully Specified Targeted IP Diagnostic Suite (FS-TIDS): A TIDS together with additional specification such as measurement packet type ("type-p" [RFC2330]), etc. which are out of scope for this document, but need to be drawn from other standards documents.

Bulk Transport Capacity: Bulk Transport Capacity Metrics evaluate an Internet path's ability to carry bulk data, such as large files, streaming (non-real time) video, and under some conditions, web images and other content. Prior efforts to define BTC metrics have been based on [RFC3148], which predates our understanding of TCP and the requirements described in Section 4. In general "Bulk Transport" indicates that performance is determined by the interplay between the network, cross traffic and congestion

control in the transport protocol. It excludes situations where performance is dominated by the RTT alone (e.g. transactions) or bottlenecks elsewhere, such as in the application itself.

IP diagnostic tests: Measurements or diagnostics to determine if packet transfer statistics meet some precomputed target.

traffic patterns: The temporal patterns or burstiness of traffic generated by applications over transport protocols such as TCP. There are several mechanisms that cause bursts at various time scales as described in Section 4.1. Our goal here is to mimic the range of common patterns (burst sizes and rates, etc), without tying our applicability to specific applications, implementations or technologies, which are sure to become stale.

Explicit Congestion Notification (ECN): See [RFC3168].

packet transfer statistics: Raw, detailed or summary statistics about packet transfer properties of the IP layer including packet losses, ECN Congestion Experienced (CE) marks, reordering, or any other properties that may be germane to transport performance.

packet loss ratio: As defined in [RFC7680].

apportioned: To divide and allocate, for example budgeting packet loss across multiple subpaths such that the losses will accumulate to less than a specified end-to-end loss ratio. Apportioning metrics is essentially the inverse of the process described in [RFC5835].

open loop: A control theory term used to describe a class of techniques where systems that naturally exhibit circular dependencies can be analyzed by suppressing some of the dependencies, such that the resulting dependency graph is acyclic.

Terminology about paths, etc. See [RFC2330] and [RFC7398] for existing terms and definitions.

data sender: Host sending data and receiving ACKs.

data receiver: Host receiving data and sending ACKs.

complete path: The end-to-end path from the data sender to the data receiver.

subpath: A portion of the complete path. Note that there is no requirement that subpaths be non-overlapping. A subpath can be as small as a single device, link or interface.

measurement point: Measurement points as described in [RFC7398].

test path: A path between two measurement points that includes a subpath of the complete path under test. If the measurement points are off path, the test path may include "test leads" between the measurement points and the subpath.

dominant bottleneck: The bottleneck that generally determines most of packet transfer statistics for the entire path. It typically determines a flow's self clock timing, packet loss and ECN Congestion Experienced (CE) marking rate, with other potential

bottlenecks having less effect on the packet transfer statistics.
See Section 4.1 on TCP properties.
front path: The subpath from the data sender to the dominant bottleneck.
back path: The subpath from the dominant bottleneck to the receiver.
return path: The path taken by the ACKs from the data receiver to the data sender.
cross traffic: Other, potentially interfering, traffic competing for network resources (bandwidth and/or queue capacity).

Properties determined by the complete path and application. These are described in more detail in Section 5.1.

Application Data Rate: General term for the data rate as seen by the application above the transport layer in bytes per second. This is the payload data rate, and explicitly excludes transport and lower level headers (TCP/IP or other protocols), retransmissions and other overhead that is not part to the total quantity of data delivered to the application.

IP rate: The actual number of IP-layer bytes delivered through a subpath, per unit time, including TCP and IP headers, retransmits and other TCP/IP overhead. Follows from IP-type-P Link Usage [RFC5136].

IP capacity: The maximum number of IP-layer bytes that can be transmitted through a subpath, per unit time, including TCP and IP headers, retransmits and other TCP/IP overhead. Follows from IP-type-P Link Capacity [RFC5136].

bottleneck IP capacity: The IP capacity of the dominant bottleneck in the forward path. All throughput maximizing protocols estimate this capacity by observing the IP rate delivered through the bottleneck. Most protocols derive their self clocks from the timing of this data. See Section 4.1 and Appendix B for more details.

implied bottleneck IP capacity: This is the bottleneck IP capacity implied by the ACKs returning from the receiver. It is determined by looking at how much application data the ACK stream at the sender reports delivered to the data receiver per unit time at various time scales. If the return path is thinning, batching or otherwise altering the ACK timing the implied bottleneck IP capacity over short time scales might be substantially larger than the bottleneck IP capacity averaged over a full RTT. Since TCP derives its clock from the data delivered through the bottleneck, the front path must have sufficient buffering to absorb any data bursts at the dimensions (size and IP rate) implied by the ACK stream, which are potentially doubled during slowstart. If the return path is not altering the ACK stream, then the implied bottleneck IP capacity will be the same as the bottleneck IP capacity. See Section 4.1 and Appendix B for more details.

sender interface rate: The IP rate which corresponds to the IP capacity of the data sender's interface. Due to sender efficiency algorithms including technologies such as TCP segmentation offload (TSO), nearly all modern servers deliver data in bursts at full interface link rate. Today 1 or 10 Gb/s are typical.

Header_overhead: The IP and TCP header sizes, which are the portion of each MTU not available for carrying application payload. Without loss of generality this is assumed to be the size for returning acknowledgments (ACKs). For TCP, the Maximum Segment Size (MSS) is the Target MTU minus the header_overhead.

Basic parameters common to models and subpath tests are defined here are described in more detail in Section 5.2. Note that these are mixed between application transport performance (excludes headers) and IP performance (which include TCP headers and retransmissions as part of the IP payload).

Network power: The observed data rate divided by the observed RTT. Network power indicates how effectively a transport protocol is filling a network.

Window [size]: The total quantity of data carried by packets in-flight plus the data represented by ACKs circulating in the network is referred to as the window. See Section 4.1. Sometimes used with other qualifiers (congestion window, cwnd or receiver window) to indicate which mechanism is controlling the window.

pipe size: A general term for number of packets needed in flight (the window size) to exactly fill some network path or subpath. It corresponds to the window size which maximizes network power. Often used with additional qualifiers to specify which path, or under what conditions, etc.

target_window_size: The average number of packets in flight (the window size) needed to meet the Target Data Rate, for the specified Target RTT, and MTU. It implies the scale of the bursts that the network might experience.

run length: A general term for the observed, measured, or specified number of packets that are (expected to be) delivered between losses or ECN Congestion Experienced (CE) marks. Nominally one over the sum of the loss and ECN CE marking probabilities, if there are independently and identically distributed.

target_run_length: The target_run_length is an estimate of the minimum number of non-congestion marked packets needed between losses or ECN Congestion Experienced (CE) marks necessary to attain the target_data_rate over a path with the specified target_RTT and target_MTU, as computed by a mathematical model of TCP congestion control. A reference calculation is shown in Section 5.2 and alternatives in Appendix A

reference target_run_length: target_run_length computed precisely by the method in Section 5.2. This is likely to be slightly more conservative than required by modern TCP implementations.

Ancillary parameters used for some tests:

derating: Under some conditions the standard models are too conservative. The modeling framework permits some latitude in relaxing or "derating" some test parameters as described in Section 5.3 in exchange for a more stringent TIDS validation procedures, described in Section 10. Models can be derated by including a multiplicative derating factor to make tests less stringent.

subpath_IP_capacity: The IP capacity of a specific subpath.

test path: A subpath of a complete path under test.

test_path_RTT: The RTT observed between two measurement points using packet sizes that are consistent with the transport protocol. This is generally MTU sized packets of the forward path, header_overhead sized packets on the return path.

test_path_pipe: The pipe size of a test path. Nominally the test_path_RTT times the test path IP_capacity.

test_window: The smallest window sufficient to meet or exceed the target_rate when operating with a pure self clock over a test path. The test_window is typically given by $\text{ceiling}(\text{target_data_rate} * \text{test_path_RTT} / (\text{target_MTU} - \text{header_overhead}))$ but see the discussion in Appendix B about the effects of channel scheduling on RTT. On some test paths the test_window may need to be adjusted slightly to compensate for the RTT being inflated by the devices that schedule packets.

The terminology below is used to define temporal patterns for test stream. These patterns are designed to mimic TCP behavior, as described in Section 4.1.

packet headway: Time interval between packets, specified from the start of one to the start of the next. e.g. If packets are sent with a 1 mS headway, there will be exactly 1000 packets per second.

burst headway: Time interval between bursts, specified from the start of the first packet one burst to the start of the first packet of the next burst. e.g. If 4 packet bursts are sent with a 1 mS burst headway, there will be exactly 4000 packets per second.

paced single packets: Send individual packets at the specified rate or packet headway.

paced bursts: Send bursts on a timer. Specify any 3 of: average data rate, packet size, burst size (number of packets) and burst headway (burst start to start). By default the bursts are assumed to occur at full sender interface rate, such that the packet

headway within each burst is the minimum supported by the sender's interface. Under some conditions it is useful to explicitly specify the packet headway within each burst.

slowstart rate: Mimic TCP slowstart by sending 4 packet paced bursts at an average data rate equal to twice the implied bottleneck IP capacity (but not more than the sender interface rate). This is a two level burst pattern described in more detail in Section 6.1. If the implied bottleneck IP capacity is more than half of the sender interface rate, slowstart rate becomes sender interface rate.

slowstart burst: Mimic one round of TCP slowstart by sending a specified number of packets in a two level burst pattern that resembles slowstart.

repeated slowstart bursts: Repeat Slowstart bursts once per target_RTT. For TCP each burst would be twice as large as the prior burst, and the sequence would end at the first ECN CE mark or lost packet. For measurement, all slowstart bursts would be the same size (nominally target_window_size but other sizes might be specified), and the ECN CE marks and lost packets are counted.

The tests described in this note can be grouped according to their applicability.

Capacity tests: Capacity tests determine if a network subpath has sufficient capacity to deliver the Target Transport Performance. As long as the test stream is within the proper envelope for the Target Transport Performance, the average packet losses or ECN Congestion Experienced (CE) marks must be below the statistical criteria computed by the model. As such, capacity tests reflect parameters that can transition from passing to failing as a consequence of cross traffic, additional presented load or the actions of other network users. By definition, capacity tests also consume significant network resources (data capacity and/or queue buffer space), and the test schedules must be balanced by their cost.

Monitoring tests: Monitoring tests are designed to capture the most important aspects of a capacity test, but without presenting excessive ongoing load themselves. As such they may miss some details of the network's performance, but can serve as a useful reduced-cost proxy for a capacity test, for example to support continuous production network monitoring.

Engineering tests: Engineering tests evaluate how network algorithms (such as AQM and channel allocation) interact with TCP-style self clocked protocols and adaptive congestion control based on packet loss and ECN Congestion Experienced (CE) marks. These tests are likely to have complicated interactions with cross traffic and under some conditions can be inversely sensitive to load. For example a test to verify that an AQM algorithm causes ECN CE marks

or packet drops early enough to limit queue occupancy may experience a false pass result in the presence of cross traffic. It is important that engineering tests be performed under a wide range of conditions, including both in situ and bench testing, and over a wide variety of load conditions. Ongoing monitoring is less likely to be useful for engineering tests, although sparse in situ testing might be appropriate.

4. Background

At the time the "Framework for IP Performance Metrics" [RFC2330] was published (1998), sound Bulk Transport Capacity (BTC) measurement was known to be well beyond our capabilities. Even when Framework for Empirical BTC Metrics [RFC3148] was published, we knew that we didn't really understand the problem. Now, by hindsight we understand why assessing BTC is such a hard problem:

- o TCP is a control system with circular dependencies - everything affects performance, including components that are explicitly not part of the test (for example, the host processing power is not in-scope of path performance tests).
- o Congestion control is a dynamic equilibrium process, similar to processes observed in chemistry and other fields. The network and transport protocols find an operating point which balances between opposing forces: the transport protocol pushing harder (raising the data rate and/or window) while the network pushes back (raising packet loss ratio, RTT and/or ECN CE marks). By design TCP congestion control keeps raising the data rate until the network gives some indication that its capacity has been exceeded by dropping packets or adding ECN CE marks. If a TCP sender accurately fills a path to its IP capacity, (e.g. the bottleneck is 100% utilized), then packet losses and ECN CE marks are mostly determined by the TCP sender and how aggressively it seeks additional capacity, and not the network itself, since the network must send exactly the signals that TCP needs to set its rate.
- o TCP's ability to compensate for network impairments (such as loss, delay and delay variation, outside of those caused by TCP itself) is directly proportional to the number of send-ACK round trip exchanges per second (i.e. inversely proportional to the RTT). As a consequence an impaired subpath may pass a short RTT local test even though it fails when the subpath is extended by an effectively perfect network to some larger RTT.
- o TCP has an extreme form of the Observer Effect (colloquially known as the Heisenberg effect). Measurement and cross traffic interact in unknown and ill defined ways. The situation is actually worse than the traditional physics problem where you can at least estimate bounds on the relative momentum of the measurement and measured particles. For network measurement you can not in

general determine even the order of magnitude of the effect. It is possible to construct measurement scenarios where the measurement traffic starves real user traffic, yielding an overly inflated measurement. The inverse is also possible: the user traffic can fill the network, such that the measurement traffic detects only minimal available capacity. You can not in general determine which scenario might be in effect, so you can not gauge the relative magnitude of the uncertainty introduced by interactions with other network traffic.

- o As a consequence of the properties listed above it is difficult, if not impossible, for two independent implementations (HW or SW) of TCP congestion control to produce equivalent performance results [RFC6576] under the same network conditions,

These properties are a consequence of the dynamic equilibrium behavior intrinsic to how all throughput maximizing protocols interact with the Internet. These protocols rely on control systems based on estimated network metrics to regulate the quantity of data to send into the network. The packet sending characteristics in turn alter the network properties estimated by the control system metrics, such that there are circular dependencies between every transmission characteristic and every estimated metric. Since some of these dependencies are nonlinear, the entire system is nonlinear, and any change anywhere causes a difficult to predict response in network metrics. As a consequence Bulk Transport Capacity metrics have not fulfilled the analytic framework envisioned in [RFC2330]

Model Based Metrics overcome these problems by making the measurement system open loop: the packet transfer statistics (akin to the network estimators) do not affect the traffic or traffic patterns (bursts), which are computed on the basis of the Target Transport Performance. A path or subpath meeting the Target Transfer Performance requirements would exhibit packet transfer statistics and estimated metrics that would not cause the control system to slow the traffic below the Target Data Rate.

4.1. TCP properties

TCP and other self clocked protocols (e.g. SCTP) carry the vast majority of all Internet data. Their dominant bulk data transport behavior is to have an approximately fixed quantity of data and acknowledgments (ACKs) circulating in the network. The data receiver reports arriving data by returning ACKs to the data sender, the data sender typically responds by sending approximately the same quantity of data back into the network. The total quantity of data plus the data represented by ACKs circulating in the network is referred to as the window. The mandatory congestion control algorithms incrementally adjust the window by sending slightly more or less data

in response to each ACK. The fundamentally important property of this system is that it is self clocked: The data transmissions are a reflection of the ACKs that were delivered by the network, the ACKs are a reflection of the data arriving from the network.

A number of protocol features cause bursts of data, even in idealized networks that can be modeled as simple queuing systems.

During slowstart the IP rate is doubled on each RTT by sending twice as much data as was delivered to the receiver during the prior RTT. Each returning ACK causes the sender to transmit twice the data the ACK reported arriving at the receiver. For slowstart to be able to fill the pipe, the network must be able to tolerate slowstart bursts up to the full pipe size inflated by the anticipated window reduction on the first loss or ECN CE mark. For example, with classic Reno congestion control, an optimal slowstart has to end with a burst that is twice the bottleneck rate for one RTT in duration. This burst causes a queue which is equal to the pipe size (i.e. the window is twice the pipe size) so when the window is halved in response to the first packet loss, the new window will be the pipe size.

Note that if the bottleneck IP rate is less than half of the capacity of the front path (which is almost always the case), the slowstart bursts will not by themselves cause significant queues anywhere else along the front path; they primarily exercise the queue at the dominant bottleneck.

Several common efficiency algorithms also cause bursts. The self clock is typically applied to groups of packets: the receiver's delayed ACK algorithm generally sends only one ACK per two data segments. Furthermore the modern senders use TCP segmentation offload (TSO) to reduce CPU overhead. The sender's software stack builds super sized TCP segments that the TSO hardware splits into MTU sized segments on the wire. The net effect of TSO, delayed ACK and other efficiency algorithms is to send bursts of segments at full sender interface rate.

Note that these efficiency algorithms are almost always in effect, including during slowstart, such that slowstart typically has a two level burst structure. Section 6.1 describes slowstart in more detail.

Additional sources of bursts include TCP's initial window [RFC6928], application pauses, channel allocation mechanisms and network devices that schedule ACKs. Appendix B describes these last two items. If the application pauses (stops reading or writing data) for some fraction of an RTT, many TCP implementations catch up to their earlier window size by sending a burst of data at the full sender

interface rate. To fill a network with a realistic application, the network has to be able to tolerate sender interface rate bursts large enough to restore the prior window following application pauses.

Although the sender interface rate bursts are typically smaller than the last burst of a slowstart, they are at a higher IP rate so they potentially exercise queues at arbitrary points along the front path from the data sender up to and including the queue at the dominant bottleneck. It is known that these bursts can hurt network performance, especially in conjunction with other queue pressure, however we are not aware of any models for how frequent sender rate bursts the network should be able to tolerate at various burst sizes.

In conclusion, to verify that a path can meet a Target Transport Performance, it is necessary to independently confirm that the path can tolerate bursts at the scales that can be caused by the above mechanisms. Three cases are believed to be sufficient:

- o Two level slowstart bursts sufficient to get connections started properly.
- o Ubiquitous sender interface rate bursts caused by efficiency algorithms. We assume 4 packet bursts to be the most common case, since it matches the effects of delayed ACK during slowstart. These bursts should be assumed not to significantly affect packet transfer statistics.
- o Infrequent sender interface rate bursts that are the maximum of the full target_window_size and the initial window size (10 segments in [RFC6928]). The Target_run_length may be derated for these large fast bursts.

If a subpath can meet the required packet loss ratio for bursts at all of these scales then it has sufficient buffering at all potential bottlenecks to tolerate any of the bursts that are likely introduced by TCP or other transport protocols.

4.2. Diagnostic Approach

A complete path of a given RTT and MTU, which are equal to or smaller than the Target RTT and equal to or larger than the Target MTU respectively, is expected to be able to attain a specified Bulk Transport Capacity when all of the following conditions are met:

1. The IP capacity is above the Target Data Rate by sufficient margin to cover all TCP/IP overheads. This can be confirmed by the tests described in Section 8.1 or any number of IP capacity tests adapted to implement MBM.
2. The observed packet transfer statistics are better than required by a suitable TCP performance model (e.g. fewer packet losses or

- ECN CE marks). See Section 8.1 or any number of low or fixed rate packet loss tests outside of MBM.
3. There is sufficient buffering at the dominant bottleneck to absorb a slowstart bursts large enough to get the flow out of slowstart at a suitable window size. See Section 8.3.
 4. There is sufficient buffering in the front path to absorb and smooth sender interface rate bursts at all scales that are likely to be generated by the application, any channel arbitration in the ACK path or any other mechanisms. See Section 8.4.
 5. When there is a slowly rising standing queue at the bottleneck the onset of packet loss has to be at an appropriate point (time or queue depth) and progressive [RFC7567]. See Section 8.2.
 6. When there is a standing queue at a bottleneck for a shared media subpath (e.g. half duplex), there must be a suitable bounds on the interaction between ACKs and data, for example due to the channel arbitration mechanism. See Section 8.2.4.

Note that conditions 1 through 4 require capacity tests for validation, and thus may need to be monitored on an ongoing basis. Conditions 5 and 6 require engineering tests, which are best performed in controlled environments such as a bench test. They won't generally fail due to load, but may fail in the field due to configuration errors, etc. and should be spot checked.

A tool that can perform many of the tests is available from [MBMSource].

4.3. New requirements relative to RFC 2330

Model Based Metrics are designed to fulfill some additional requirements that were not recognized at the time RFC 2330 was written [RFC2330]. These missing requirements may have significantly contributed to policy difficulties in the IP measurement space. Some additional requirements are:

- o IP metrics must be actionable by the ISP - they have to be interpreted in terms of behaviors or properties at the IP or lower layers, that an ISP can test, repair and verify.
- o Metrics should be spatially composable, such that measures of concatenated paths should be predictable from subpaths.
- o Metrics must be vantage point invariant over a significant range of measurement point choices, including off path measurement points. The only requirements on MP selection should be that the RTT between the MPs is below some reasonable bound, and that the effects of the "test leads" connecting MPs to the subpath under test can be calibrated out of the measurements. The latter might be accomplished if the test leads are effectively ideal or their properties can be deducted from the measurements between

the MPs. While many of tests require that the test leads have at least as much IP capacity as the subpath under test, some do not, for example Background Packet Transfer Tests described in Section 8.1.3.

- o Metric measurements should be repeatable by multiple parties with no specialized access to MPs or diagnostic infrastructure. It should be possible for different parties to make the same measurement and observe the same results. In particular it is specifically important that both a consumer (or their delegate) and ISP be able to perform the same measurement and get the same result. Note that vantage independence is key to meeting this requirement.

5. Common Models and Parameters

5.1. Target End-to-end parameters

The target end-to-end parameters are the Target Data Rate, Target RTT and Target MTU as defined in Section 3. These parameters are determined by the needs of the application or the ultimate end user and the complete Internet path over which the application is expected to operate. The target parameters are in units that make sense to upper layers: payload bytes delivered to the application, above TCP. They exclude overheads associated with TCP and IP headers, retransmits and other protocols (e.g. DNS). Note that IP-based network services include TCP headers and retransmissions as part of delivered payload, and this difference is recognized in calculations below (`header_overhead`).

Other end-to-end parameters defined in Section 3 include the effective bottleneck data rate, the sender interface data rate and the TCP and IP header sizes.

The `target_data_rate` must be smaller than all subpath IP capacities by enough headroom to carry the transport protocol overhead, explicitly including retransmissions and an allowance for fluctuations in TCP's actual data rate. Specifying a `target_data_rate` with insufficient headroom is likely to result in brittle measurements having little predictive value.

Note that the target parameters can be specified for a hypothetical path, for example to construct TIDS designed for bench testing in the absence of a real application; or for a live in situ test of production infrastructure.

The number of concurrent connections is explicitly not a parameter to this model. If a subpath requires multiple connections in order to

meet the specified performance, that must be stated explicitly and the procedure described in Section 6.4 applies.

5.2. Common Model Calculations

The Target Transport Performance is used to derive the `target_window_size` and the reference `target_run_length`.

The `target_window_size`, is the average window size in packets needed to meet the `target_rate`, for the specified `target_RTT` and `target_MTU`. It is given by:

$$\text{target_window_size} = \text{ceiling}(\text{target_rate} * \text{target_RTT} / (\text{target_MTU} - \text{header_overhead}))$$

`Target_run_length` is an estimate of the minimum required number of unmarked packets that must be delivered between losses or ECN Congestion Experienced (CE) marks, as computed by a mathematical model of TCP congestion control. The derivation here follows [MSM097], and by design is quite conservative.

Reference `target_run_length` is derived as follows: assume the `subpath_IP_capacity` is infinitesimally larger than the `target_data_rate` plus the required `header_overhead`. Then `target_window_size` also predicts the onset of queuing. A larger window will cause a standing queue at the bottleneck.

Assume the transport protocol is using standard Reno style Additive Increase, Multiplicative Decrease (AIMD) congestion control [RFC5681] (but not Appropriate Byte Counting [RFC3465]) and the receiver is using standard delayed ACKs. Reno increases the window by one packet every `pipe_size` worth of ACKs. With delayed ACKs this takes 2 Round Trip Times per increase. To exactly fill the pipe, the spacing of losses must be no closer than when the peak of the AIMD sawtooth reached exactly twice the `target_window_size`. Otherwise, the multiplicative window reduction triggered by the loss would cause the network to be under-filled. Following [MSM097] the number of packets between losses must be the area under the AIMD sawtooth. They must be no more frequent than every 1 in $((3/2)*\text{target_window_size})*(2*\text{target_window_size})$ packets, which simplifies to:

$$\text{target_run_length} = 3*(\text{target_window_size}^2)$$

Note that this calculation is very conservative and is based on a number of assumptions that may not apply. Appendix A discusses these assumptions and provides some alternative models. If a different model is used, a FS-TIDS must document the actual method for

computing `target_run_length` and ratio between alternate `target_run_length` and the reference `target_run_length` calculated above, along with a discussion of the rationale for the underlying assumptions.

These two parameters, `target_window_size` and `target_run_length`, directly imply most of the individual parameters for the tests in Section 8.

5.3. Parameter Derating

Since some aspects of the models are very conservative, the MBM framework permits some latitude in derating test parameters. Rather than trying to formalize more complicated models we permit some test parameters to be relaxed as long as they meet some additional procedural constraints:

- o The FS-TIDS must document and justify the actual method used to compute the derated metric parameters.
- o The validation procedures described in Section 10 must be used to demonstrate the feasibility of meeting the Target Transport Performance with infrastructure that just barely passes the derated tests.
- o The validation process for a FS-TIDS itself must be documented in such a way that other researchers can duplicate the validation experiments.

Except as noted, all tests below assume no derating. Tests where there is not currently a well established model for the required parameters explicitly include derating as a way to indicate flexibility in the parameters.

5.4. Test Preconditions

Many tests have preconditions which are required to assure their validity. Examples include: the presence or non-presence of cross traffic on specific subpaths; negotiating ECN; and appropriate preamble packet stream to testing to put reactive network elements into the proper states [RFC7312]. If preconditions are not properly satisfied for some reason, the tests should be considered to be inconclusive. In general it is useful to preserve diagnostic information as to why the preconditions were not met, and any test data that was collected even if it is not useful for the intended test. Such diagnostic information and partial test data may be useful for improving the test or test procedures themselves.

It is important to preserve the record that a test was scheduled, because otherwise precondition enforcement mechanisms can introduce

sampling bias. For example, canceling tests due to cross traffic on subscriber access links might introduce sampling bias in tests of the rest of the network by reducing the number of tests during peak network load.

Test preconditions and failure actions must be specified in a FS-TIDS.

6. Generating test streams

Many important properties of Model Based Metrics, such as vantage independence, are a consequence of using test streams that have temporal structures that mimic TCP or other transport protocols running over a complete path. As described in Section 4.1, self clocked protocols naturally have burst structures related to the RTT and pipe size of the complete path. These bursts naturally get larger (contain more packets) as either the Target RTT or Target Data Rate get larger, or the Target MTU gets smaller. An implication of these relationships is that test streams generated by running self clocked protocols over short subpaths may not adequately exercise the queuing at any bottleneck to determine if the subpath can support the full Target Transport Performance over the complete path.

Failing to authentically mimic TCP's temporal structure is part of the reason why simple performance tools such as iPerf, netperf, nc, etc have the reputation of yielding false pass results over short test paths, even when some subpath has a flaw.

The definitions in Section 3 are sufficient for most test streams. We describe the slowstart and standing queue test streams in more detail.

In conventional measurement practice stochastic processes are used to eliminate many unintended correlations and sample biases. However MBM tests are designed to explicitly mimic temporal correlations caused by network or protocol elements themselves. Some portions of these systems, such as traffic arrival (test scheduling) are naturally stochastic. Other behaviors, such as back-to-back packet transmissions, are dominated by implementation specific deterministic effects. Although these behaviors always contain non-deterministic elements and might be modeled stochastically, these details typically do not contribute significantly to the overall system behavior. Furthermore, it is known that real protocols are subject to failures caused by network property estimators suffering from bias due to correlation in their own traffic. For example TCP's RTT estimator used to determine the Retransmit Time Out (RTO), can be fooled by periodic cross traffic or start-stop applications. For these reasons many details of the test streams are specified deterministically.

It may prove useful to introduce fine grained noise sources into the models used for generating test streams in an update of Model Based Metrics, but the complexity is not warranted at the time this document was written.

6.1. Mimicking slowstart

TCP slowstart has a two level burst structure as shown in Figure 2. The fine time structure is caused by efficiency algorithms that deliberately batch work (CPU, channel allocation, etc) to better amortize certain network and host overheads. ACKs passing through the return path typically cause the sender to transmit small bursts of data at full sender interface rate. For example TCP Segmentation Offload (TSO) and Delayed Acknowledgment both contribute to this effect. During slowstart these bursts are at the same headway as the returning ACKs, but are typically twice as large (e.g. having twice as much data) as the ACK reported was delivered to the receiver. Due to variations in delayed ACK and algorithms such as Appropriate Byte Counting [RFC3465], different pairs of senders and receivers produce slightly different burst patterns. Without loss of generality, we assume each ACK causes 4 packet sender interface rate bursts at an average headway equal to the ACK headway, and corresponding to sending at an average rate equal to twice the effective bottleneck IP rate. Each slowstart burst consists of a series of 4 packet sender interface rate bursts such that the total number of packets is the current window size (as of the last packet in the burst).

The coarse time structure is due to each RTT being a reflection of the prior RTT. For real transport protocols, each slowstart burst is twice as large (twice the window) as the previous burst but is spread out in time by the network bottleneck, such that each successive RTT exhibits the same effective bottleneck IP rate. The slowstart phase ends on the first lost packet or ECN mark, which is intended to happen after successive slowstart bursts merge in time: the next burst starts before the bottleneck queue is fully drained and the prior burst is complete.

For diagnostic tests described below we preserve the fine time structure but manipulate the coarse structure of the slowstart bursts (burst size and headway) to measure the ability of the dominant bottleneck to absorb and smooth slowstart bursts.

Note that a stream of repeated slowstart bursts has three different average rates, depending on the averaging time interval. At the finest time scale (a few packet times at the sender interface) the peak of the average IP rate is the same as the sender interface rate; at a medium timescale (a few ACK times at the dominant bottleneck) the peak of the average IP rate is twice the implied bottleneck IP

capacity; and at time scales longer than the `target_RTT` and when the burst size is equal to the `target_window_size`, the average rate is equal to the `target_data_rate`. This pattern corresponds to repeating the last RTT of TCP slowstart when delayed ACK and sender side byte counting are present but without the limits specified in Appropriate Byte Counting [RFC3465].

time ==> (- equals one packet)

Fine time structure of the packet stream:

|<>| sender interface rate bursts (typically 3 or 4 packets)
|<===>| burst headway (from the ACK headway)

_____repeating sender_____/
rate bursts

Coarse (RTT level) time structure of the packet stream:

----- ...

|<=====>| slowstart burst size (from the window)
|<=====>| slowstart headway
(from the RTT)

_____ /
one slowstart burst

_____ ...
Repeated slowstart bursts

Multiple levels of Slowstart Bursts

Figure 2

6.2. Constant window pseudo CBR

Implement pseudo constant bit rate by running a standard self clocked protocol such as TCP with a fixed window size. If that window size is `test_window`, the data rate will be slightly above the `target_rate`.

Since the `test_window` is constrained to be an integer number of packets, for small RTTs or low data rates there may not be sufficiently precise control over the data rate. Rounding the `test_window` up (as defined above) is likely to result in data rates that are higher than the target rate, but reducing the window by one packet may result in data rates that are too small. Also cross traffic potentially raises the RTT, implicitly reducing the rate.

Cross traffic that raises the RTT nearly always makes the test more strenuous (more demanding for the network path).

Note that Constant window pseudo CBR (and Scanned window pseudo CBR in the next section) both rely on a self clock which is at least partially derived from the properties of the subnet under test. This introduces the possibility that the subnet under test exhibits behaviors such as extreme RTT fluctuations that prevent these algorithms from accurately controlling data rates.

A FS-TIDS specifying a constant window CBR test must explicitly indicate under what conditions errors in the data rate cause tests to be inconclusive. Conventional paced measurement traffic may be more appropriate for these environments.

6.3. Scanned window pseudo CBR

Scanned window pseudo CBR is similar to the constant window CBR described above, except the window is scanned across a range of sizes designed to include two key events, the onset of queuing and the onset of packet loss or ECN CE marks. The window is scanned by incrementing it by one packet every $2 \times \text{target_window_size}$ delivered packets. This mimics the additive increase phase of standard Reno TCP congestion avoidance when delayed ACKs are in effect. Normally the window increases separated by intervals slightly longer than twice the `target_RTT`.

There are two ways to implement this test: one built by applying a window clamp to standard congestion control in a standard protocol such as TCP and the other built by stiffening a non-standard transport protocol. When standard congestion control is in effect, any losses or ECN CE marks cause the transport to revert to a window smaller than the clamp such that the scanning clamp loses control the window size. The NPAD pathdiag tool is an example of this class of algorithms [Pathdiag].

Alternatively a non-standard congestion control algorithm can respond to losses by transmitting extra data, such that it maintains the specified window size independent of losses or ECN CE marks. Such a stiffened transport explicitly violates mandatory Internet congestion control [RFC5681] and is not suitable for in situ testing. It is only appropriate for engineering testing under laboratory conditions. The Windowed Ping tool implements such a test [WPING]. The tool described in the paper has been updated.[mpingSource]

The test procedures in Section 8.2 describe how to partition the scans into regions and how to interpret the results.

6.4. Concurrent or channelized testing

The procedures described in this document are only directly applicable to single stream measurement, e.g. one TCP connection or measurement stream. In an ideal world, we would disallow all performance claims based multiple concurrent streams, but this is not practical due to at least two issues. First, many very high rate link technologies are channelized and at last partially pin the flow to channel mapping to minimize packet reordering within flows. Second, TCP itself has scaling limits. Although the former problem might be overcome through different design decisions, the later problem is more deeply rooted.

All congestion control algorithms that are philosophically aligned with the standard [RFC5681] (e.g. claim some level of TCP compatibility, friendliness or fairness) have scaling limits, in the sense that as a long fast network (LFN) with a fixed RTT and MTU gets faster, these congestion control algorithms get less accurate and as a consequence have difficulty filling the network [CCscaling]. These properties are a consequence of the original Reno AIMD congestion control design and the requirement in [RFC5681] that all transport protocols have similar responses to congestion.

There are a number of reasons to want to specify performance in terms of multiple concurrent flows, however this approach is not recommended for data rates below several megabits per second, which can be attained with run lengths under 10000 packets on many paths. Since the required run length goes as the square of the data rate, at higher rates the run lengths can be unreasonably large, and multiple flows might be the only feasible approach.

If multiple flows are deemed necessary to meet aggregate performance targets then this must be stated in both the design of the TIDS and in any claims about network performance. The IP diagnostic tests must be performed concurrently with the specified number of connections. For the tests that use bursty test streams, the bursts should be synchronized across streams unless there is a priori knowledge that the applications have some explicit mechanism to stagger their own bursts. In the absences of an explicit mechanism to stagger bursts many network and application artifacts will sometimes implicitly synchronize bursts. A test that does not control burst synchronization may be prone to false pass results for some applications.

7. Interpreting the Results

7.1. Test outcomes

To perform an exhaustive test of a complete network path, each test of the TIDS is applied to each subpath of the complete path. If any subpath fails any test then a standard transport protocol running over the complete path can also be expected to fail to attain the Target Transport Performance under some conditions.

In addition to passing or failing, a test can be deemed to be inconclusive for a number of reasons. Proper instrumentation and treatment of inconclusive outcomes is critical to the accuracy and robustness of Model Based Metrics. Tests can be inconclusive if the precomputed traffic pattern or data rates were not accurately generated; the measurement results were not statistically significant; and others causes such as failing to meet some required preconditions for the test. See Section 5.4

For example consider a test that implements Constant Window Pseudo CBR (Section 6.2) by adding rate controls and detailed IP packet transfer instrumentation to TCP (e.g. [RFC4898]). TCP includes built in control systems which might interfere with the sending data rate. If such a test meets the required packet transfer statistics (e.g. run length) while failing to attain the specified data rate it must be treated as an inconclusive result, because we can not a priori determine if the reduced data rate was caused by a TCP problem or a network problem, or if the reduced data rate had a material effect on the observed packet transfer statistics.

Note that for capacity tests, if the observed packet transfer statistics meet the statistical criteria for failing (accepting hypothesis H1 in Section 7.2), the test can be considered to have failed because it doesn't really matter that the test didn't attain the required data rate.

The really important new properties of MBM, such as vantage independence, are a direct consequence of opening the control loops in the protocols, such that the test stream does not depend on network conditions or IP packets received. Any mechanism that introduces feedback between the path's measurements and the test stream generation is at risk of introducing nonlinearities that spoil these properties. Any exceptional event that indicates that such feedback has happened should cause the test to be considered inconclusive.

One way to view inconclusive tests is that they reflect situations where a test outcome is ambiguous between limitations of the network

and some unknown limitation of the IP diagnostic test itself, which may have been caused by some uncontrolled feedback from the network.

Note that procedures that attempt to search the target parameter space to find the limits on some parameter such as `target_data_rate` are at risk of breaking the location independent properties of Model Based Metrics, if any part of the boundary between passing and inconclusive or failing results is sensitive to RTT (which is normally the case). For example the maximum data rate for a marginal link (e.g. exhibiting excess errors) is likely to be sensitive to the `test_path_RTT`. The maximum observed data rate over the test path has very little value for predicting the maximum rate over a different path.

One of the goals for evolving TIDS designs will be to keep sharpening distinction between inconclusive, passing and failing tests. The criteria for for passing, failing and inconclusive tests must be explicitly stated for every test in the TIDS or FS-TIDS.

One of the goals of evolving the testing process, procedures, tools and measurement point selection should be to minimize the number of inconclusive tests.

It may be useful to keep raw packet transfer statistics and ancillary metrics [RFC3148] for deeper study of the behavior of the network path and to measure the tools themselves. Raw packet transfer statistics can help to drive tool evolution. Under some conditions it might be possible to re-evaluate the raw data for satisfying alternate Target Transport Performance. However it is important to guard against sampling bias and other implicit feedback which can cause false results and exhibit measurement point vantage sensitivity. Simply applying different delivery criteria based on a different Target Transport Performance is insufficient if the test traffic patterns (bursts, etc.) does not match the alternate Target Transport Performance.

7.2. Statistical criteria for estimating `run_length`

When evaluating the observed `run_length`, we need to determine appropriate packet stream sizes and acceptable error levels for efficient measurement. In practice, can we compare the empirically estimated packet loss and ECN Congestion Experienced (CE) marking ratios with the targets as the sample size grows? How large a sample is needed to say that the measurements of packet transfer indicate a particular run length is present?

The generalized measurement can be described as recursive testing: send packets (individually or in patterns) and observe the packet

transfer performance (packet loss ratio or other metric, any marking we define).

As each packet is sent and measured, we have an ongoing estimate of the performance in terms of the ratio of packet loss or ECN CE mark to total packets (i.e. an empirical probability). We continue to send until conditions support a conclusion or a maximum sending limit has been reached.

We have a `target_mark_probability`, 1 mark per `target_run_length`, where a "mark" is defined as a lost packet, a packet with ECN CE mark, or other signal. This constitutes the null Hypothesis:

H0: no more than one mark in `target_run_length` =
 $3 * (\text{target_window_size})^2$ packets

and we can stop sending packets if on-going measurements support accepting H0 with the specified Type I error = α (= 0.05 for example).

We also have an alternative Hypothesis to evaluate: if performance is significantly lower than the `target_mark_probability`. Based on analysis of typical values and practical limits on measurement duration, we choose four times the H0 probability:

H1: one or more marks in $(\text{target_run_length}/4)$ packets

and we can stop sending packets if measurements support rejecting H0 with the specified Type II error = β (= 0.05 for example), thus preferring the alternate hypothesis H1.

H0 and H1 constitute the Success and Failure outcomes described elsewhere in the memo, and while the ongoing measurements do not support either hypothesis the current status of measurements is inconclusive.

The problem above is formulated to match the Sequential Probability Ratio Test (SPRT) [Wald45] and [Montgomery90]. Note that as originally framed the events under consideration were all manufacturing defects. In networking, ECN CE marks and lost packets are not defects but signals, indicating that the transport protocol should slow down.

The Sequential Probability Ratio Test also starts with a pair of hypothesis specified as above:

H0: p_0 = one defect in `target_run_length`
H1: p_1 = one defect in `target_run_length/4`

As packets are sent and measurements collected, the tester evaluates the cumulative defect count against two boundaries representing H0 Acceptance or Rejection (and acceptance of H1):

Acceptance line: $X_a = -h_1 + s \cdot n$

Rejection line: $X_r = h_2 + s \cdot n$

where n increases linearly for each packet sent and

$$\begin{aligned} h_1 &= \{ \log((1-\alpha)/\beta) \} / k \\ h_2 &= \{ \log((1-\beta)/\alpha) \} / k \\ k &= \log\{ (p_1(1-p_0)) / (p_0(1-p_1)) \} \\ s &= [\log\{ (1-p_0)/(1-p_1) \}] / k \end{aligned}$$

for p_0 and p_1 as defined in the null and alternative Hypotheses statements above, and α and β as the Type I and Type II errors.

The SPRT specifies simple stopping rules:

- o $X_a < \text{defect_count}(n) < X_r$: continue testing
- o $\text{defect_count}(n) \leq X_a$: Accept H0
- o $\text{defect_count}(n) \geq X_r$: Accept H1

The calculations above are implemented in the R-tool for Statistical Analysis [Rtool] , in the add-on package for Cross-Validation via Sequential Testing (CVST) [CVST].

Using the equations above, we can calculate the minimum number of packets (n) needed to accept H0 when x defects are observed. For example, when $x = 0$:

$$\begin{aligned} X_a = 0 &= -h_1 + s \cdot n \\ \text{and } n &= h_1 / s \end{aligned}$$

Note that the derivations in [Wald45] and [Montgomery90] differ. Montgomery's simplified derivation of SPRT may assume a Bernoulli processes, where the packet loss probabilities are independent and identically distributed, making the SPRT more accessible. Wald's seminal paper showed that this assumption is not necessary. It helps to remember that the goal of SPRT is not to estimate the value of the packet loss rate, but only whether or not the packet loss ratio is likely low enough (when we accept the H0 null hypothesis) yielding success; or too high (when we accept the H1 alternate hypothesis) yielding failure.

7.3. Reordering Tolerance

All tests must be instrumented for packet level reordering [RFC4737]. However, there is no consensus for how much reordering should be acceptable. Over the last two decades the general trend has been to make protocols and applications more tolerant to reordering (see for example [RFC4015]), in response to the gradual increase in reordering in the network. This increase has been due to the deployment of technologies such as multithreaded routing lookups and Equal Cost MultiPath (ECMP) routing. These techniques increase parallelism in network and are critical to enabling overall Internet growth to exceed Moore's Law.

Note that transport retransmission strategies can trade off reordering tolerance vs how quickly they can repair losses vs overhead from spurious retransmissions. In advance of new retransmission strategies we propose the following strawman: Transport protocols should be able to adapt to reordering as long as the reordering extent is not more than the maximum of one quarter window or 1 mS, whichever is larger. (These values come from experience prototyping Early Retransmit [RFC5827] and related algorithms. They agree with the values being proposed for "RACK: a time-based fast loss detection algorithm" [I-D.ietf-tcpm-rack].) Within this limit on reorder extent, there should be no bound on reordering density.

By implication, recording which is less than these bounds should not be treated as a network impairment. However [RFC4737] still applies: reordering should be instrumented and the maximum reordering that can be properly characterized by the test (because of the bound on history buffers) should be recorded with the measurement results.

Reordering tolerance and diagnostic limitations, such as the size of the history buffer used to diagnose packets that are way out-of-order, must be specified in a FSTIDS.

8. IP Diagnostic Tests

The IP diagnostic tests below are organized according to the technique used to generate the test stream as described in Section 6. All of the results are evaluated in accordance with Section 7, possibly with additional test specific criteria.

We also introduce some combined tests which are more efficient when networks are expected to pass, but conflate diagnostic signatures when they fail.

8.1. Basic Data Rate and Packet Transfer Tests

We propose several versions of the basic data rate and packet transfer statistics test that differ in how the data rate is controlled. The data can be paced on a timer, or window controlled (and self clocked). The first two tests implicitly confirm that `sub_path` has sufficient raw capacity to carry the `target_data_rate`. They are recommended for relatively infrequent testing, such as an installation or periodic auditing process. The third, background packet transfer statistics, is a low rate test designed for ongoing monitoring for changes in subpath quality.

8.1.1. Delivery Statistics at Paced Full Data Rate

Confirm that the observed run length is at least the `target_run_length` while relying on timer to send data at the `target_rate` using the procedure described in in Section 6.1 with a burst size of 1 (single packets) or 2 (packet pairs).

The test is considered to be inconclusive if the packet transmission can not be accurately controlled for any reason.

RFC 6673 [RFC6673] is appropriate for measuring packet transfer statistics at full data rate.

8.1.2. Delivery Statistics at Full Data Windowed Rate

Confirm that the observed run length is at least the `target_run_length` while sending at an average rate approximately equal to the `target_data_rate`, by controlling (or clamping) the window size of a conventional transport protocol to `test_window`.

Since losses and ECN CE marks cause transport protocols to reduce their data rates, this test is expected to be less precise about controlling its data rate. It should not be considered inconclusive as long as at least some of the round trips reached the full `target_data_rate` without incurring losses or ECN CE marks. To pass this test the network must deliver `target_window_size` packets in `target_RTT` time without any losses or ECN CE marks at least once per two `target_window_size` round trips, in addition to meeting the run length statistical test.

8.1.3. Background Packet Transfer Statistics Tests

The background run length is a low rate version of the target target rate test above, designed for ongoing lightweight monitoring for changes in the observed subpath run length without disrupting users. It should be used in conjunction with one of the above full rate

tests because it does not confirm that the subpath can support raw data rate.

RFC 6673 [RFC6673] is appropriate for measuring background packet transfer statistics.

8.2. Standing Queue Tests

These engineering tests confirm that the bottleneck is well behaved across the onset of packet loss, which typically follows after the onset of queuing. Well behaved generally means lossless for transient queues, but once the queue has been sustained for a sufficient period of time (or reaches a sufficient queue depth) there should be a small number of losses or ECN CE marks to signal to the transport protocol that it should reduce its window or data rate. Losses that are too early can prevent the transport from averaging at the `target_data_rate`. Losses that are too late indicate that the queue might not have an appropriate AQM [RFC7567] and as a consequence subject to bufferbloat [wikiBloat]. Queues without AQM have the potential to inflict excess delays on all flows sharing the bottleneck. Excess losses (more than half of the window) at the onset of loss make loss recovery problematic for the transport protocol. Non-linear, erratic or excessive RTT increases suggest poor interactions between the channel acquisition algorithms and the transport self clock. All of the tests in this section use the same basic scanning algorithm, described here, but score the link or subpath on the basis of how well it avoids each of these problems.

Some network technologies rely on virtual queues or other techniques to meter traffic without adding any queuing delay, in which case the data rate will vary with the window size all the way up to the onset of load induced packet loss or ECN CE marks. For these technologies, the discussion of queuing in Section 6.3 does not apply, but it is still necessary to confirm that the onset of losses or ECN CE marks be at an appropriate point and progressive. If the network bottleneck does not introduce significant queuing delay, modify the procedure described in Section 6.3 to start the scan at a window equal to or slightly smaller than the `test_window`.

Use the procedure in Section 6.3 to sweep the window across the onset of queuing and the onset of loss. The tests below all assume that the scan emulates standard additive increase and delayed ACK by incrementing the window by one packet for every $2 \times \text{target_window_size}$ packets delivered. A scan can typically be divided into three regions: below the onset of queuing, a standing queue, and at or beyond the onset of loss.

Below the onset of queuing the RTT is typically fairly constant, and the data rate varies in proportion to the window size. Once the data rate reaches the subpath IP rate, the data rate becomes fairly constant, and the RTT increases in proportion to the increase in window size. The precise transition across the start of queuing can be identified by the maximum network power, defined to be the ratio data rate over the RTT. The network power can be computed at each window size, and the window with the maximum is taken as the start of the queuing region.

If there is random background loss (e.g. bit errors, etc), precise determination of the onset of queue induced packet loss may require multiple scans. Above the onset of queuing loss, all transport protocols are expected to experience periodic losses determined by the interaction between the congestion control and AQM algorithms. For standard congestion control algorithms the periodic losses are likely to be relatively widely spaced and the details are typically dominated by the behavior of the transport protocol itself. For the stiffened transport protocols case (with non-standard, aggressive congestion control algorithms) the details of periodic losses will be dominated by how the window increase function responds to loss.

8.2.1. Congestion Avoidance

A subpath passes the congestion avoidance standing queue test if more than `target_run_length` packets are delivered between the onset of queuing (as determined by the window with the maximum network power as described above) and the first loss or ECN CE mark. If this test is implemented using a standard congestion control algorithm with a clamp, it can be performed in situ in the production internet as a capacity test. For an example of such a test see [Pathdiag].

For technologies that do not have conventional queues, use the `test_window` in place of the onset of queuing. i.e. A subpath passes the congestion avoidance standing queue test if more than `target_run_length` packets are delivered between start of the scan at `test_window` and the first loss or ECN CE mark.

8.2.2. Bufferbloat

This test confirms that there is some mechanism to limit buffer occupancy (e.g. that prevents bufferbloat). Note that this is not strictly a requirement for single stream bulk transport capacity, however if there is no mechanism to limit buffer queue occupancy then a single stream with sufficient data to deliver is likely to cause the problems described in [RFC7567], and [wikiBloat]. This may cause only minor symptoms for the dominant flow, but has the potential to make the subpath unusable for other flows and applications.

Pass if the onset of loss occurs before a standing queue has introduced more delay than twice `target_RTT`, or other well defined and specified limit. Note that there is not yet a model for how much standing queue is acceptable. The factor of two chosen here reflects a rule of thumb. In conjunction with the previous test, this test implies that the first loss should occur at a queuing delay which is between one and two times the `target_RTT`.

Specified RTT limits that are larger than twice the `target_RTT` must be fully justified in the FS-TIDS.

8.2.3. Non excessive loss

This test confirms that the onset of loss is not excessive. Pass if losses are equal or less than the increase in the cross traffic plus the test stream window increase since the previous RTT. This could be restated as non-decreasing total throughput of the subpath at the onset of loss. (Note that when there is a transient drop in subpath throughput and there is not already a standing queue, a subpath that passes other queue tests in this document will have sufficient queue space to hold one full RTT worth of data).

Note that token bucket policers will not pass this test, which is as intended. TCP often stumbles badly if more than a small fraction of the packets are dropped in one RTT. Many TCP implementations will require a timeout and slowstart to recover their self clock. Even if they can recover from the massive losses the sudden change in available capacity at the bottleneck wastes serving and front path capacity until TCP can adapt to the new rate [Policing].

8.2.4. Duplex Self Interference

This engineering test confirms a bound on the interactions between the forward data path and the ACK return path when they share a half duplex link.

Some historical half duplex technologies had the property that each direction held the channel until it completely drained its queue. When a self clocked transport protocol, such as TCP, has data and ACKs passing in opposite directions through such a link, the behavior often reverts to stop-and-wait. Each additional packet added to the window raises the observed RTT by two packet times, once as the additional packet passes through the data path, and once for the additional delay incurred by the ACK waiting on the return path.

The duplex self interference test fails if the RTT rises by more than a fixed bound above the expected queuing time computed from the excess window divided by the subpath IP Capacity. This bound must be

smaller than $\text{target_RTT}/2$ to avoid reverting to stop and wait behavior. (e.g. Data packets and ACKs both have to be released at least twice per RTT.)

8.3. Slowstart tests

These tests mimic slowstart: data is sent at twice the effective bottleneck rate to exercise the queue at the dominant bottleneck.

8.3.1. Full Window slowstart test

This is a capacity test to confirm that slowstart is not likely to exit prematurely. Send slowstart bursts that are $\text{target_window_size}$ total packets.

Accumulate packet transfer statistics as described in Section 7.2 to score the outcome. Pass if it is statistically significant that the observed number of good packets delivered between losses or ECN CE marks is larger than the target_run_length . Fail if it is statistically significant that the observed interval between losses or ECN CE marks is smaller than the target_run_length .

It is deemed inconclusive if the elapsed time to send the data burst is not less than half of the time to receive the ACKs. (i.e. It is acceptable to send data too fast, but sending it slower than twice the actual bottleneck rate as indicated by the ACKs is deemed inconclusive). The headway for the slowstart bursts should be the target_RTT .

Note that these are the same parameters as the Sender Full Window burst test, except the burst rate is at slowstart rate, rather than sender interface rate.

8.3.2. Slowstart AQM test

Do a continuous slowstart (send data continuously at twice the implied IP bottleneck capacity), until the first loss, stop, allow the network to drain and repeat, gathering statistics on how many packets were delivered before the loss, the pattern of losses, maximum observed RTT and window size. Justify the results. There is not currently sufficient theory justifying requiring any particular result, however design decisions that affect the outcome of this tests also affect how the network balances between long and short flows (the "mice vs elephants" problem). The queue sojourn time for the first packet delivered after the first loss should be at least one half of the target_RTT .

This is an engineering test: It should be performed on a quiescent network or testbed, since cross traffic has the potential to change the results in ill defined ways.

8.4. Sender Rate Burst tests

These tests determine how well the network can deliver bursts sent at sender's interface rate. Note that this test most heavily exercises the front path, and is likely to include infrastructure may be out of scope for an access ISP, even though the bursts might be caused by ACK compression, thinning or channel arbitration in the access ISP. See Appendix B.

Also, there are a several details about sender interface rate bursts that are not fully defined here. These details, such as the assumed sender interface rate, should be explicitly stated is a FS-TIDS.

Current standards permit TCP to send full window bursts following an application pause. (Congestion Window Validation [RFC2861] and updates to support Rate-Limited Traffic [RFC7661], are not required). Since full window bursts are consistent with standard behavior, it is desirable that the network be able to deliver such bursts, otherwise application pauses will cause unwarranted losses. Note that the AIMD sawtooth requires a peak window that is twice `target_window_size`, so the worst case burst may be $2 * \text{target_window_size}$.

It is also understood in the application and serving community that interface rate bursts have a cost to the network that has to be balanced against other costs in the servers themselves. For example TCP Segmentation Offload (TSO) reduces server CPU in exchange for larger network bursts, which increase the stress on network buffer memory. Some newer TCP implementations can pace traffic at scale [`TSO_pacing`][`TSO_fq_pacing`]. It remains to be determined if and how quickly these changes will be deployed.

There is not yet theory to unify these costs or to provide a framework for trying to optimize global efficiency. We do not yet have a model for how much server rate bursts should be tolerated by the network. Some bursts must be tolerated by the network, but it is probably unreasonable to expect the network to be able to efficiently deliver all data as a series of bursts.

For this reason, this is the only test for which we encourage derating. A TIDS could include a table of pairs of derating parameters: burst sizes and how much each burst size is permitted to reduce the run length, relative to to the `target_run_length`.

8.5. Combined and Implicit Tests

Combined tests efficiently confirm multiple network properties in a single test, possibly as a side effect of normal content delivery. They require less measurement traffic than other testing strategies at the cost of conflating diagnostic signatures when they fail. These are by far the most efficient for monitoring networks that are nominally expected to pass all tests.

8.5.1. Sustained Bursts Test

The sustained burst test implements a combined worst case version of all of the capacity tests above. It is simply:

Send `target_window_size` bursts of packets at server interface rate with `target_RTT` burst headway (burst start to next burst start). Verify that the observed packet transfer statistics meets the `target_run_length`.

Key observations:

- o The subpath under test is expected to go idle for some fraction of the time, determined by the difference between the time to drain the queue at the `subpath_IP_capacity`, and the `target_RTT`. If the queue does not drain completely it may be an indication that the subpath has insufficient IP capacity or that there is some other problem with the test (e.g. inconclusive).
- o The burst sensitivity can be derated by sending smaller bursts more frequently. E.g. send `target_window_size*derate` packet bursts every `target_RTT*derate`, where "derate" is less than one.
- o When not derated, this test is the most strenuous capacity test.
- o A subpath that passes this test is likely to be able to sustain higher rates (close to `subpath_IP_capacity`) for paths with RTTs significantly smaller than the `target_RTT`.
- o This test can be implemented with instrumented TCP [RFC4898], using a specialized measurement application at one end [MBMSource] and a minimal service at the other end [RFC0863] [RFC0864].
- o This test is efficient to implement, since it does not require per-packet timers, and can make use of TSO in modern NIC hardware.
- o If a subpath is known to pass the Standing Queue engineering tests (particularly that it has a progressive onset of loss at an appropriate queue depth), then the Sustained Burst Test is sufficient to assure that the subpath under test will not impair Bulk Transport Capacity at the target performance under all conditions. See Section 8.2 for a discussion of the standing queue tests.

Note that this test is clearly independent of the subpath RTT, or other details of the measurement infrastructure, as long as the measurement infrastructure can accurately and reliably deliver the required bursts to the subpath under test.

8.5.2. Passive Measurements

Any non-throughput maximizing application, such as fixed rate streaming media, can be used to implement passive or hybrid (defined in [RFC7799]) versions of Model Based Metrics with some additional instrumentation and possibly a traffic shaper or other controls in the servers. The essential requirement is that the data transmission be constrained such that even with arbitrary application pauses and bursts, the data rate and burst sizes stay within the envelope defined by the individual tests described above.

If the application's serving data rate can be constrained to be less than or equal to the `target_data_rate` and the serving_RTT (the RTT between the sender and client) is less than the `target_RTT`, this constraint is most easily implemented by clamping the transport window size to `serving_window_clamp`, set to the `test_window`, computed for the actual serving path.

Under the above constraints the `serving_window_clamp` will limit the both the serving data rate and burst sizes to be no larger than the procedures in Section 8.1.2 and Section 8.4 or Section 8.5.1. Since the serving RTT is smaller than the `target_RTT`, the worst case bursts that might be generated under these conditions will be smaller than called for by Section 8.4 and the sender rate burst sizes are implicitly derated by the `serving_window_clamp` divided by the `target_window_size` at the very least. (Depending on the application behavior, the data might be significantly smoother than specified by any of the burst tests.)

In an alternative implementation the data rate and bursts might be explicitly controlled by a programmable traffic shaper or pacing at the sender. This would provide better control over transmissions but is more complicated to implement, although the required technology is available [TSO_pacing][TSO_fq_pacing].

Note that these techniques can be applied to any content delivery that can operate at a constrained data rate to inhibit TCP equilibrium behavior.

Furthermore note that Dynamic Adaptive Streaming over HTTP (DASH) is generally in conflict with passive Model Based Metrics measurement, because it is a rate maximizing protocol. It can still meet the requirement here if the rate can be capped, for example by knowing a

priori the maximum rate needed to deliver a particular piece of content.

9. An Example

In this section we illustrate a TIDS designed to confirm that an access ISP can reliably deliver HD video from multiple content providers to all of their customers. With modern codecs, minimal HD video (720p) generally fits in 2.5 Mb/s. Due to their geographical size, network topology and modem characteristics the ISP determines that most content is within a 50 ms RTT of their users (This example RTT is sufficient to cover the propagation delay to continental Europe or either US coast with low delay modems or somewhat smaller geographical regions if the modems require additional delay to implement advanced compression and error recovery).

2.5 Mb/s over a 50 ms path

End-to-End Parameter	value	units
target_rate	2.5	Mb/s
target_RTT	50	ms
target_MTU	1500	bytes
header_overhead	64	bytes
target_window_size	11	packets
target_run_length	363	packets

Table 1

Table 1 shows the default TCP model with no derating, and as such is quite conservative. The simplest TIDS would be to use the sustained burst test, described in Section 8.5.1. Such a test would send 11 packet bursts every 50ms, and confirming that there was no more than 1 packet loss per 33 bursts (363 total packets in 1.650 seconds).

Since this number represents is the entire end-to-end loss budget, independent subpath tests could be implemented by apportioning the packet loss ratio across subpaths. For example 50% of the losses might be allocated to the access or last mile link to the user, 40% to the network interconnections with other ISPs and 1% to each internal hop (assuming no more than 10 internal hops). Then all of the subpaths can be tested independently, and the spatial composition of passing subpaths would be expected to be within the end-to-end loss budget.

9.1. Observations about applicability

Guidance on deploying and using MBM belong in a future document. However this example illustrates some the issues that may need to be considered.

Note that another ISP, with different geographical coverage, topology or modem technology may need to assume a different target_RTT, and as a consequence different target_window_size and target_run_length, even for the same target_data rate. One of the implications of this is that infrastructure shared by multiple ISPs, such as inter-exchange points (IXPs) and other interconnects may need to be evaluated on the basis of the most stringent target_window_size and target_run_length of any participating ISP. One way to do this might be to choose target parameters for evaluating such shared infrastructure on the basis of a hypothetical reference path that does not necessarily match any actual paths.

Testing interconnects has generally been problematic: conventional performance tests run between measurement points adjacent to either side of the interconnect are not generally useful. Unconstrained TCP tests, such as iPerf [iPerf] are usually overly aggressive due to the small RTT (often less than 1 mS). With a short RTT these tools are likely to report inflated data rates because on a short RTT these tools can tolerate very high packet loss ratios and can push other cross traffic off of the network. As a consequence these measurements are useless for predicting actual user performance over longer paths, and may themselves be quite disruptive. Model Based Metrics solves this problem. The interconnect can be evaluated with the same TIDS as other subpaths. Continuing our example, if the interconnect is apportioned 40% of the losses, 11 packet bursts sent every 50mS should have fewer than one loss per 82 bursts (902 packets).

10. Validation

Since some aspects of the models are likely to be too conservative, Section 5.2 permits alternate protocol models and Section 5.3 permits test parameter derating. If either of these techniques are used, we require demonstrations that such a TIDS can robustly detect subpaths that will prevent authentic applications using state-of-the-art protocol implementations from meeting the specified Target Transport Performance. This correctness criteria is potentially difficult to prove, because it implicitly requires validating a TIDS against all possible paths and subpaths. The procedures described here are still experimental.

We suggest two approaches, both of which should be applied: first, publish a fully open description of the TIDS, including what assumptions were used and how it was derived, such that the research community can evaluate the design decisions, test them and comment on their applicability; and second, demonstrate that applications do meet the Target Transport Performance when running over a network testbed which has the tightest possible constraints that still allow the tests in the TIDS to pass.

This procedure resembles an epsilon-delta proof in calculus. Construct a test network such that all of the individual tests of the TIDS pass by only small (infinitesimal) margins, and demonstrate that a variety of authentic applications running over real TCP implementations (or other protocols as appropriate) meets the Target Transport Performance over such a network. The workloads should include multiple types of streaming media and transaction oriented short flows (e.g. synthetic web traffic).

For example, for the HD streaming video TIDS described in Section 9, the IP capacity should be exactly the header_overhead above 2.5 Mb/s, the per packet random background loss ratio should be 1/363, for a run length of 363 packets, the bottleneck queue should be 11 packets and the front path should have just enough buffering to withstand 11 packet interface rate bursts. We want every one of the TIDS tests to fail if we slightly increase the relevant test parameter, so for example sending a 12 packet burst should cause excess (possibly deterministic) packet drops at the dominant queue at the bottleneck. This network has the tightest possible constraints that can be expected to pass the TIDS, yet it should be possible for a real application using a stock TCP implementation in the vendor's default configuration to attain 2.5 Mb/s over an 50 mS path.

The most difficult part of setting up such a testbed is arranging for it to have the tightest possible constraints that still allow it to pass the individual tests. Two approaches are suggested: constraining (configuring) the network devices not to use all available resources (e.g. by limiting available buffer space or data rate); and pre-loading subpaths with cross traffic. Note that it is important that a single tightly constrained environment just barely passes all tests, otherwise there is a chance that TCP can exploit extra latitude in some parameters (such as data rate) to partially compensate for constraints in other parameters (queue space, or vice-versa).

To the extent that a TIDS is used to inform public dialog it should be fully publicly documented, including the details of the tests, what assumptions were used and how it was derived. All of the details of the validation experiment should also be published with

sufficient detail for the experiments to be replicated by other researchers. All components should either be open source or fully described proprietary implementations that are available to the research community.

11. Security Considerations

Measurement is often used to inform business and policy decisions, and as a consequence is potentially subject to manipulation. Model Based Metrics are expected to be a huge step forward because equivalent measurements can be performed from multiple vantage points, such that performance claims can be independently validated by multiple parties.

Much of the acrimony in the Net Neutrality debate is due to the historical lack of any effective vantage independent tools to characterize network performance. Traditional methods for measuring Bulk Transport Capacity are sensitive to RTT and as a consequence often yield very different results when run local to an ISP or interconnect and when run over a customer's complete path. Neither the ISP nor customer can repeat the others measurements, leading to high levels of distrust and acrimony. Model Based Metrics are expected to greatly improve this situation.

Note that in situ measurements sometimes requires sending synthetic measurement traffic between arbitrary locations in the network, and as such are potentially attractive platforms for launching DDOS attacks. All active measurement tools and protocols must be designed to minimize the opportunities for these misuses. See the discussion in section 7 of [RFC7594].

Some of the tests described in the note are not intended for frequent network monitoring since they have the potential to cause high network loads and might adversely affect other traffic.

This document only describes a framework for designing Fully Specified Targeted IP Diagnostic Suite. Each FS-TIDS must include its own security section.

12. Acknowledgments

Ganga Maguluri suggested the statistical test for measuring loss probability in the target run length. Alex Gilgur and Merry Mou for helping with the statistics.

Meredith Whittaker for improving the clarity of the communications.

Ruediger Geib provided feedback which greatly improved the document.

This work was inspired by Measurement Lab: open tools running on an open platform, using open tools to collect open data. See <http://www.measurementlab.net/>

13. IANA Considerations

This document has no actions for IANA.

14. Informative References

- [RFC0863] Postel, J., "Discard Protocol", STD 21, RFC 863, May 1983.
- [RFC0864] Postel, J., "Character Generator Protocol", STD 22, RFC 864, May 1983.
- [RFC2330] Paxson, V., Almes, G., Mahdavi, J., and M. Mathis, "Framework for IP Performance Metrics", RFC 2330, May 1998.
- [RFC2861] Handley, M., Padhye, J., and S. Floyd, "TCP Congestion Window Validation", RFC 2861, June 2000.
- [RFC3148] Mathis, M. and M. Allman, "A Framework for Defining Empirical Bulk Transfer Capacity Metrics", RFC 3148, July 2001.
- [RFC3168] Ramakrishnan, K., Floyd, S., and D. Black, "The Addition of Explicit Congestion Notification (ECN) to IP", RFC 3168, DOI 10.17487/RFC3168, September 2001, <<http://www.rfc-editor.org/info/rfc3168>>.
- [RFC3465] Allman, M., "TCP Congestion Control with Appropriate Byte Counting (ABC)", RFC 3465, February 2003.
- [RFC4015] Ludwig, R. and A. Gurtov, "The Eifel Response Algorithm for TCP", RFC 4015, February 2005.
- [RFC4737] Morton, A., Ciavattone, L., Ramachandran, G., Shalunov, S., and J. Perser, "Packet Reordering Metrics", RFC 4737, November 2006.
- [RFC4898] Mathis, M., Heffner, J., and R. Raghunarayan, "TCP Extended Statistics MIB", RFC 4898, May 2007.
- [RFC5136] Chimento, P. and J. Ishac, "Defining Network Capacity", RFC 5136, February 2008.

- [RFC5681] Allman, M., Paxson, V., and E. Blanton, "TCP Congestion Control", RFC 5681, September 2009.
- [RFC5827] Allman, M., Avrachenkov, K., Ayesta, U., Blanton, J., and P. Hurtig, "Early Retransmit for TCP and Stream Control Transmission Protocol (SCTP)", RFC 5827, DOI 10.17487/RFC5827, May 2010, <<http://www.rfc-editor.org/info/rfc5827>>.
- [RFC5835] Morton, A. and S. Van den Berghe, "Framework for Metric Composition", RFC 5835, April 2010.
- [RFC6049] Morton, A. and E. Stephan, "Spatial Composition of Metrics", RFC 6049, January 2011.
- [RFC6576] Geib, R., Ed., Morton, A., Fardid, R., and A. Steinmitz, "IP Performance Metrics (IPPM) Standard Advancement Testing", BCP 176, RFC 6576, DOI 10.17487/RFC6576, March 2012, <<http://www.rfc-editor.org/info/rfc6576>>.
- [RFC6673] Morton, A., "Round-Trip Packet Loss Metrics", RFC 6673, August 2012.
- [RFC6928] Chu, J., Dukkupati, N., Cheng, Y., and M. Mathis, "Increasing TCP's Initial Window", RFC 6928, DOI 10.17487/RFC6928, April 2013, <<http://www.rfc-editor.org/info/rfc6928>>.
- [RFC7312] Fabini, J. and A. Morton, "Advanced Stream and Sampling Framework for IP Performance Metrics (IPPM)", RFC 7312, August 2014.
- [RFC7398] Bagnulo, M., Burbridge, T., Crawford, S., Eardley, P., and A. Morton, "A Reference Path and Measurement Points for Large-Scale Measurement of Broadband Performance", RFC 7398, February 2015.
- [RFC7567] Baker, F., Ed. and G. Fairhurst, Ed., "IETF Recommendations Regarding Active Queue Management", BCP 197, RFC 7567, DOI 10.17487/RFC7567, July 2015, <<http://www.rfc-editor.org/info/rfc7567>>.
- [RFC7594] Eardley, P., Morton, A., Bagnulo, M., Burbridge, T., Aitken, P., and A. Akhter, "A Framework for Large-Scale Measurement of Broadband Performance (LMAP)", RFC 7594, DOI 10.17487/RFC7594, September 2015, <<http://www.rfc-editor.org/info/rfc7594>>.

- [RFC7661] Fairhurst, G., Sathiaselalan, A., and R. Secchi, "Updating TCP to Support Rate-Limited Traffic", RFC 7661, DOI 10.17487/RFC7661, October 2015, <<http://www.rfc-editor.org/info/rfc7661>>.
- [RFC7680] Almes, G., Kalidindi, S., Zekauskas, M., and A. Morton, Ed., "A One-Way Loss Metric for IP Performance Metrics (IPPM)", STD 82, RFC 7680, DOI 10.17487/RFC7680, January 2016, <<http://www.rfc-editor.org/info/rfc7680>>.
- [RFC7799] Morton, A., "Active and Passive Metrics and Methods (with Hybrid Types In-Between)", RFC 7799, DOI 10.17487/RFC7799, May 2016, <<http://www.rfc-editor.org/info/rfc7799>>.
- [I-D.ietf-tcpm-rack] Cheng, Y., Cardwell, N., and N. Dukkkipati, "RACK: a time-based fast loss detection algorithm for TCP", draft-ietf-tcpm-rack-02 (work in progress), March 2017.
- [MSMO97] Mathis, M., Semke, J., Mahdavi, J., and T. Ott, "The Macroscopic Behavior of the TCP Congestion Avoidance Algorithm", Computer Communications Review volume 27, number3, July 1997.
- [WPING] Mathis, M., "Windowed Ping: An IP Level Performance Diagnostic", INET 94, June 1994.
- [mpingSource] Fan, X., Mathis, M., and D. Hamon, "Git Repository for mping: An IP Level Performance Diagnostic", Sept 2013, <<https://github.com/m-lab/mping>>.
- [MBMSource] Hamon, D., Stuart, S., and H. Chen, "Git Repository for Model Based Metrics", Sept 2013, <<https://github.com/m-lab/MBM>>.
- [Pathdiag] Mathis, M., Heffner, J., O'Neil, P., and P. Siemsen, "Pathdiag: Automated TCP Diagnosis", Passive and Active Measurement , June 2008.
- [iPerf] Wikipedia Contributors, , "iPerf", Wikipedia, The Free Encyclopedia , cited March 2015, <<http://en.wikipedia.org/w/index.php?title=Iperf&oldid=649720021>>.

- [Wald45] Wald, A., "Sequential Tests of Statistical Hypotheses", The Annals of Mathematical Statistics, Vol. 16, No. 2, pp. 117-186, Published by: Institute of Mathematical Statistics, Stable URL: <http://www.jstor.org/stable/2235829>, June 1945.
- [Montgomery90] Montgomery, D., "Introduction to Statistical Quality Control - 2nd ed.", ISBN 0-471-51988-X, 1990.
- [Rtool] R Development Core Team, , "R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL <http://www.R-project.org/>", , 2011.
- [CVST] Krueger, T. and M. Braun, "R package: Fast Cross-Validation via Sequential Testing", version 0.1, 11 2012.
- [AFD] Pan, R., Breslau, L., Prabhakar, B., and S. Shenker, "Approximate fairness through differential dropping", SIGCOMM Comput. Commun. Rev. 33, 2, April 2003.
- [wikiBloat] Wikipedia, , "Bufferbloat", <http://en.wikipedia.org/w/index.php?title=Bufferbloat&oldid=608805474>, March 2015.
- [CCscaling] Fernando, F., Doyle, J., and S. Steven, "Scalable laws for stable network congestion control", Proceedings of Conference on Decision and Control, <http://www.ee.ucla.edu/~paganini>, December 2001.
- [TSO_pacing] Corbet, J., "TSO sizing and the FQ scheduler", LWN.net <https://lwn.net/Articles/564978/>, Aug 2013.
- [TSO_fq_pacing] Dumazet, E. and Y. Chen, "TSO, fair queuing, pacing: three's a charm", Proceedings of IETF 88, TCPM WG <https://www.ietf.org/proceedings/88/slides/slides-88-tcpm-9.pdf>, Nov 2013.
- [Policing] Flach, T., Papageorge, P., Terzis, A., Pedrosa, L., Cheng, Y., Karim, T., Katz-Bassett, E., and R. Govindan, "An Internet-Wide Analysis of Traffic Policing", ACM SIGCOMM , August 2016.

Appendix A. Model Derivations

The reference `target_run_length` described in Section 5.2 is based on very conservative assumptions: that all excess data in flight (window) above the `target_window_size` contributes to a standing queue that raises the RTT, and that classic Reno congestion control with delayed ACKs are in effect. In this section we provide two alternative calculations using different assumptions.

It may seem out of place to allow such latitude in a measurement method, but this section provides offsetting requirements.

The estimates provided by these models make the most sense if network performance is viewed logarithmically. In the operational Internet, data rates span more than 8 orders of magnitude, RTT spans more than 3 orders of magnitude, and packet loss ratio spans at least 8 orders of magnitude if not more. When viewed logarithmically (as in decibels), these correspond to 80 dB of dynamic range. On an 80 dB scale, a 3 dB error is less than 4% of the scale, even though it represents a factor of 2 in untransformed parameter.

This document gives a lot of latitude for calculating `target_run_length`, however people designing a TIDS should consider the effect of their choices on the ongoing tussle about the relevance of "TCP friendliness" as an appropriate model for Internet capacity allocation. Choosing a `target_run_length` that is substantially smaller than the reference `target_run_length` specified in Section 5.2 strengthens the argument that it may be appropriate to abandon "TCP friendliness" as the Internet fairness model. This gives developers incentive and permission to develop even more aggressive applications and protocols, for example by increasing the number of connections that they open concurrently.

A.1. Queueless Reno

In Section 5.2 models were derived based on the assumption that the subpath IP rate matches the target rate plus overhead, such that the excess window needed for the AIMD sawtooth causes a fluctuating queue at the bottleneck.

An alternate situation would be a bottleneck where there is no significant queue and losses are caused by some mechanism that does not involve extra delay, for example by the use of a virtual queue as done in Approximate Fair Dropping [AFD]. A flow controlled by such a bottleneck would have a constant RTT and a data rate that fluctuates in a sawtooth due to AIMD congestion control. Assume the losses are being controlled to make the average data rate meet some goal which

is equal or greater than the `target_rate`. The necessary run length to meet the `target_rate` can be computed as follows:

For some value of `Wmin`, the window will sweep from `Wmin` packets to `2*Wmin` packets in `2*Wmin` RTT (due to delayed ACK). Unlike the queuing case where `Wmin = target_window_size`, we want the average of `Wmin` and `2*Wmin` to be the `target_window_size`, so the average data rate is the target rate. Thus we want $Wmin = (2/3) * target_window_size$.

Between losses each sawtooth delivers $(1/2)(Wmin + 2*Wmin)(2Wmin)$ packets in `2*Wmin` round trip times.

Substituting these together we get:

$$target_run_length = (4/3)(target_window_size^2)$$

Note that this is 44% of the `reference_run_length` computed earlier. This makes sense because under the assumptions in Section 5.2 the AMID sawtooth caused a queue at the bottleneck, which raised the effective RTT by 50%.

Appendix B. The effects of ACK scheduling

For many network technologies simple queuing models don't apply: the network schedules, thins or otherwise alters the timing of ACKs and data, generally to raise the efficiency of the channel allocation algorithms when confronted with relatively widely spaced small ACKs. These efficiency strategies are ubiquitous for half duplex, wireless and broadcast media.

Altering the ACK stream by holding or thinning ACKs typically has two consequences: it raises the implied bottleneck IP capacity, making the fine grained slowstart bursts either faster or larger and it raises the effective RTT by the average time that the ACKs and data are delayed. The first effect can be partially mitigated by re-clocking ACKs once they are beyond the bottleneck on the return path to the sender, however this further raises the effective RTT.

The most extreme example of this sort of behavior would be a half duplex channel that is not released as long as the endpoint currently holding the channel has more traffic (data or ACKs) to send. Such environments cause self clocked protocols under full load to revert to extremely inefficient stop and wait behavior. The channel constrains the protocol to send an entire window of data as a single contiguous burst on the forward path, followed by the entire window of ACKs on the return path.

If a particular return path contains a subpath or device that alters the timing of the ACK stream, then the entire front path from the sender up to the bottleneck must be tested at the burst parameters implied by the ACK scheduling algorithm. The most important parameter is the Implied Bottleneck IP Capacity, which is the average rate at which the ACKs advance `snd.una`. Note that thinning the ACK stream (relying on the cumulative nature of `seg.ack` to permit discarding some ACKs) causes most TCP implementations to send interface rate bursts to offset the longer times between ACKs in order to maintain the average data rate.

Note that due to ubiquitous self clocking in Internet protocols, ill conceived channel allocation mechanisms are likely to increase the queuing stress on the front path because they cause larger full sender rate data bursts.

Holding data or ACKs for channel allocation or other reasons (such as forward error correction) always raises the effective RTT relative to the minimum delay for the path. Therefore it may be necessary to replace `target_RTT` in the calculation in Section 5.2 by an `effective_RTT`, which includes the `target_RTT` plus a term to account for the extra delays introduced by these mechanisms.

Appendix C. Version Control

This section to be removed prior to publication.

Formatted: Thu Apr 7 18:12:37 PDT 2016

Authors' Addresses

Matt Mathis
Google, Inc
1600 Amphitheater Parkway
Mountain View, California 94043
USA

Email: mattmathis@google.com

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

Phone: +1 732 420 1571
Email: acmorton@att.com