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Empirical Bulk Transfer Capacity

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Abstract:

Bulk Transport Capacity (BTC) is a measure of a network's ability to transfer significant quantities of data with a single congestion-aware transport connection (e.g., TCP). The intuitive definition of BTC is the expected long term average data rate (bits per second) of a single ideal TCP implementation over the path in question. However, there are many congestion control algorithms (and hence transport implementations) permitted by IETF standards. This diversity in transport algorithms creates a difficulty for standardizing BTC metrics because the allowed diversity is sufficient to lead to situations where different implementations will yield non-comparable measures -- and potentially fail the formal tests for being a metric.

This document defines a framework for standardizing multiple BTC

metrics that parallel the permitted transport diversity. Two approaches are used. First, each BTC metric must be much more tightly specified than the typical IETF protocol. Pseudo-code or reference implementations are expected to be the norm. Second, each BTC methodology is expected to collect some ancillary metrics which are potentially useful to support analytical models of BTC.

1. Introduction

Bulk Transport Capacity (BTC) is a measure of a network's ability to transfer significant quantities of data with a single congestion-aware transport connection (e.g., TCP). For many applications the BTC of the underlying network dominates the overall elapsed time for the application and thus dominates the performance as perceived by a user. Examples of such applications include FTP, and the world wide web when delivering large images or documents.

The intuitive definition of BTC is the expected long term average data rate (bits per second) of a single ideal TCP implementation over the path in question.

Central to the notion of bulk transport capacity is the idea that all transport protocols should have similar responses to congestion in the Internet. Indeed the only form of equity significantly deployed in the Internet today is that the vast majority of all traffic is carried by TCP implementations sharing common congestion control algorithms largely due to a shared developmental heritage.

[RFC2001.bis] specifies the standard congestion control algorithms used by these TCP implementations. Even though this document is a (proposed) standard, it permits considerable latitude in implementation. This latitude is by design, to encourage ongoing evolution in congestion control algorithms.

This legal diversity in transport algorithms creates a difficulty for standardizing BTC metrics because the allowed diversity is sufficient to lead to situations where different implementations will yield non-comparable measures -- and potentially fail the formal tests for being a metric.

@@@ A more serious problem is that most of the existing CC algorithms
@ do not assure that improving the properties of a path improves the
@ measure of that path. That is existing TCP implementations do not
@ always have performance that monotonically increase with true path
@ capacity.
#
OK. I'll leave that to you... I think it needs said and supported
with some explanation. --allman
@ Next pass --MM--

Furthermore congestion control and related areas, including Integrated services[@@], differentiated services[@@] and Internet traffic analysis[@@] are all currently receiving a lot of attention from the research community. It is very likely that we will see new experimental congestion control algorithms in the near future. In addition, explicit congestion notification (ECN) [RFC98] is being tested for Internet deployment. We do not yet know how any of these developments might affect BTC metrics.

This document defines a framework for standardizing multiple BTC metrics that parallel the permitted transport diversity. Two approaches are used. First, each BTC metric must be much more tightly specified than the typical IETF protocol. Pseudo-code or reference implementations are expected to be the norm. Second, each BTC methodology is expected to collect some ancillary metrics which are potentially useful to support analytical models of BTC.

For example, the models in [PFTK98, MSMO97, OKM96a, Lak94] all predict bulk performance based on path properties such as loss rate, round trip time, etc. A BTC methodology which also provides ancillary measures of these properties is stronger because agreement with the analytical models can be used to corroborate the direct BTC measurement results.

More importantly these ancillary metrics are expected to be useful for resolving disparity between different BTC metrics. For example, a path that predominantly experiences clustered packet losses is likely to exhibit vastly different measures from BTC metrics that mimic Tahoe, Reno, NewReno, and SACK TCP algorithms [FF96]. The differences in the BTC metrics over such a path might be diagnosed by an ancillary measure of loss clustering.

Furthermore there are some path properties which are best measured as ancillary metrics to a transport protocol. Examples of such properties include bottleneck queue limits or the tendency to reorder packets. These are difficult or impossible to measure at low rates and unsafe to measure at rates higher than the bulk transport capacity of the path.

It is expected that at some point in the future there will exist an A-frame [RFC2330] which will unify all simple path metrics (e.g., segment loss rates, round trip time) and BTC ancillary metrics (e.g. queue size and packet reordering) with different versions of BTC metrics (e.g., that parallel Reno or SACK TCP).

2. Congestion Control Algorithms

Nearly all TCP implementations in use today are based on congestion control algorithms published in [Jac88] and further

refined in [RFC2001,RFC2001.bis]. In addition to the basic notion of using an ACK clock, TCP (and therefore BTC) implements five standard congestion control algorithms: Congestion Avoidance, Retransmission timeouts, Slow-start, Fast Retransmit and Fast Recovery. All BTC implementations must use these algorithms as they are defined in [RFC2001.bis]. However, in all cases a BTC metric must more tightly specify these algorithms, as discussed below.

2.1 Congestion Avoidance

The Congestion Avoidance algorithm drives the steady-state bulk transfer behavior of TCP. It calls for opening the congestion window (cwnd) by a constant additive amount during each round trip time (RTT), and closing it by a constant multiplicative fraction on congestion, as indicated by lost segments. The window closing is specified to be half the number of outstanding data segments in flight when loss is detected. A BTC metric must specify the following Congestion Avoidance details:

> The exact algorithm for incrementing cwnd is left to the implementer. Several candidate algorithms are outlined in [RFC2001.bis]. In addition, some of these algorithms include some rounding. For these reasons, the exact algorithm for increasing cwnd during congestion avoidance must be fully specified for each BTC metric defined.
>
> [RFC2001.bis] permits an extra plus one segment window adjustment following the multiplicative closing of cwnd. This is because [RFC2001.bis] allows a single invocation of the Slow-Start algorithm when when cwnd equals ssthresh at the end of recovery.

2.2 Retransmission Timeouts

In order to provide reliable data delivery, TCP resends a segment if the ACK for the given segment does not arrive before the retransmission timer (RTO) fires. A BTC metric must implement an RTO timer to trigger retransmissions not handled by the fast retransmit algorithm. Such retransmissions can have a large impact on the measured capacity. Calculating the RTO is subject to a number of details that are not standardized. When implementing a BTC metric the details of the RTO calculation, how and when the clock is set, as well as the clock granularity must be fully documented.

2.3 Slow Start

Slow start is part of TCP's transient behavior. It is used to quickly bring new or recently restarted connections up to an appropriate congestion window. In addition, slow start is used to

restart the ACK clock after a retransmission timeout. A BTC implementation must use the slow start algorithm, as specified by [RFC2001.bis]. The slow start algorithm is used while the congestion window (cwnd) is less than the slow start threshold (ssthresh). However, whether to use slow start or congestion avoidance when cwnd equals ssthresh is left to the implementer by [RFC2001.bis]. This detail must be specified in every specific BTC metric definition.

2.4 Fast Retransmit/Fast Recovery

The Fast Retransmit/Fast Recovery algorithms are used to infer segment loss before the RTO expires. A BTC implementation must implement the algorithms as defined in [RFC2001.bis].

In Reno TCP, Fast Retransmit and Fast Recovery are used to support the Congestion Avoidance algorithm during recovery from lost segments. During Fast Recovery, the data receiver sends duplicated acknowledgments. The data sender uses these duplicate ACKs to detect loss, to estimate the quantity of data in the network still pending delivery and to clock out new data in an effort to keep the ACK clock running.

2.5 Advanced Recovery Algorithms

It has been observed that under some conditions the Fast Retransmit and Fast Recovery algorithms do not reliably preserve TCP's Self-Clock, causing unpredictable or unstable TCP performance [Lak94@@@check, Flo95]. Simulations of reference TCP implementations have uncovered situations where incidental changes in other parts of the network have a large effect on performance [MM96a]. Other simulations have shown that under some conditions, slightly better networks (higher bandwidth, lower delay or less load from other connections) yield lower throughput.
@@@ This is pretty easy to construct, but has it been published?
# Not that I can think of off the top of my head... Maybe a concrete
# example to back up the claim? --allman

[RFC2001.bis] allows a TCP implementation to use more robust loss recovery algorithms, such as NewReno type algorithms [FH98,FF96,Hoe96] and SACK-based algorithms [FF96,MM96a,MM96b]. While allowing these algorithms, [RFC2001.bis] does not define any such algorithm and therefore, a BTC metric that implements advanced recovery algorithms must fully specify the details.

Note that since TCP based on standard Fast Retransmit and Fast Recovery sometimes exhibits erratic performance [MM96a], these algorithms may prove to be unsuitable for use in a metric.
Ouch... I know what you're saying, but... If the goal is to see what
congestion-aware transport connection yields, I think the above is a
little harsh given the current standardized CC algorithms.

2.6 Segment Size

The actual segment size, or method of choosing a segment size (e.g., path MTU discovery [RFC1191]) and the number of header bytes assumed to be prepended to each segment must be specified. In addition if the segment size is artificially limited to less than the path MTU this must be indicated.

3 Ancillary Metrics

The following ancillary metrics should be implemented in every BTC that can exhibit the relevant behaviors. Alternatively, the BTC implementation should provide enough information that the following information can be gathered in post-processing (e.g., by providing a segment trace of the connection).

3.1 Congestion Avoidance Capacity

Define a pure "Congestion Avoidance Capacity" (CAC) metric to be the data rate (bits per second) of a fully specified implementation of the Congestion Avoidance algorithm, subject to the restriction that the Retransmission Timeout and Slow-Start algorithms are not invoked. The CAC metric is defined to have no meaning across Retransmission Timeouts or Slow-Start (except the single segment Slow-Start that is permitted to follow recovery).

In principle a CAC metric would be an ideal BTC metric. But there is a rather substantial difficulty with using it as such. The Self-Clocking of the Congestion Avoidance algorithm can be very fragile, depending on the specific details of the Fast Retransmit, Fast Recovery or advanced recovery algorithms above.

When TCP looses Self-Clock it is reestablished through a retransmission timeout and Slow-Start. These algorithms nearly always take more time than Congestion Avoidance would have taken.

It is easily observed that unless the network loses an entire window of data (which would clearly require a retransmit timeout) TCP missed some opportunity to send data. That is, if TCP experiences a timeout after losing any partial window of data, it must have received at least one ACK that was generated after some of the partial data was delivered, but did not trigger transmitting any new data. Much recent research in congestion control (e.g., FACK[MM96a], NewReno[FH98], [LowWindow]) can be characterized as making TCP's Self-Clock more tenacious, while preserving fairness under adverse conditions. This work is often motivated by how poorly current TCP implementations perform under some conditions, often due to repeated clock loss. Since this is an active research area, different TCP implementations have rather considerable differences in their ability to preserve Self-Clock.

3.2 Ancillary metrics relating to the preservation of Self-Clock

Since loosing the clock can have a large effect on the overall BTC, and the clock is itself fragile in ways that are very dependent on the recovery algorithm, it is important that the transitions between timer driven and Self-Clocked operation be instrumented.

3.2.1 Lost transmission opportunities

If the last event before a timeout was the receipt of an ACK that did not trigger a retransmission, the possibility exists that some other congestion control algorithm would have successfully preserved the Self-Clock. In this event, instrumenting key parts of the BTC state (e.g., cwnd) may lead to further improvements in congestion control algorithms.

Note that in the absence of knowledge about the future, it is not possible to design an algorithm that never misses transmission opportunities. However, there are ever more subtle ways to gauge network state, and to estimate if a given ACK is likely to be the last.

3.2.2 Loosing an entire window

If an entire window of data (or ACKs) is lost, there will be no returning ACKs to clock out additional data. This condition can be detected if the last event before a timeout was a data transmission triggered by an ACK. The loss of an entire window of data/ACKs forces recovery to be via a Retransmission Timeout and Slow-Start.

Losing an entire window of data implies an outage with a duration at least as long as a round trip time. Such an outage can not be diagnosed with low rate metrics and is unsafe to diagnose at higher rates than the BTC. Therefore all BTC metrics at should instrument and report losses of an entire window of data.

There are some conditions, such as at very small window, in which there is a significant probability that an entire window can be legitimately lost through individual random losses.

3.2.3 Heroic clock preservation

All algorithms that permit a given BTC to sustain Self-Clock when other algorithms might not, should be instrumented. Furthermore, the details of the algorithms used must be fully documented.

> BTC metrics that can sustain Self-Clock in the presence of multiple losses within one round trip should instrument the loss distribution, such that the performance of Reno style bulk transport can be estimated.

BTC algorithms that can trigger fast retransmits earlier than following three duplicate acknowledgments (e.g. at small window [LowWindow]), should instrument and fully document these events as well.

3.2.4 False timeouts

All false timeouts, (where the transmission timer expires before the ACK for some previously transmitted data arrives) should be instrumented when possible. Note that depending upon how the BTC metric implements sequence numbers, this may be difficult to detect.

3.3 Ancillary metrics relating to flow based path properties

All BTC metrics provide unique vantage points for instrumenting certain path properties relating to closely spaced packets. As in the case of RTT duration outages, these can be impossible to diagnose at low rates (less than 1 packet per RTT) and inappropriate to test at rates above the BTC.

All BTC metrics should instrument packet reordering. The severity of the reordering can be classified as one of three different cases, each of which should be instrumented.

Packets that are only slightly out of order should not trigger retransmission, but they may affect the window calculation. BTC metrics must document how slightly out-of-order packets affect the congestion window calculation. The frequency and distance out of sequence must be instrumented for all out-of-order packets.

If packets are sufficiently out-of-order, the Fast Retransmit algorithm will be invoked in advance of the delayed packet's late arrival. These events must be instrumented.
Even though the the late arriving packet will complete recovery, the the window must still be reduced by half.

Under some rare conditions packets have been observed that are far out of order - sometimes many seconds late [Pax97b].
These should always be instrumented.

The BTC should instrument the maximum cwnd observed during congestion avoidance and slow start. A TCP running over the same path must have sufficient sender buffer space and receiver window (and window shift [RFC1323]) to cover this cwnd.

There are several other path properties that one might measure within a BTC metric. For example, with an embedded one-way delay metric it may be possible to measure how queueing delay and

and (RED) drop probabilities are correlated to window size. These are all open research questions.

3.4 Ancillary metrics pertaining to MTU discovery

Under some conditions, BTC can be very sensitive to segment size. In addition to instrumenting the segment size, a BTC metric should indicate how it was selected: by path MTU discovery [RFC1191], a manual control, system default, or the maximum MTU for the interface.

Note that the most popular LAN technologies have smaller MTUs than nearly all WAN technologies. As a consequence, it is difficult to measure the true performance of a wide area path without subjecting it to the smaller MTU of the LAN.

3.4 Ancillary metrics as calibration checks

Unlike low rate metrics, BTC must have explicit checks that the test platform is not the bottleneck, either due to insufficient tester data rate or buffer space.

Ideally all queues within the tester should be instrumented. All packets dropped within the tester should be instrumented as tester failures, invalidating a measurement.

The maximum queue lengths should be instrumented. Any significant queue may indicate that the tester itself has insufficient burst data rate, and is slightly smoothing the data into the network.

3.4.3 Validate Reverse path load

@@@@ What happens to a BTC when the reverse path is congested? Is this identical to TCP? What should happen? How should it be instrumented?

#
Some implementations (mine!) have an annoying feature whereby ACK loss
looks just like data loss. This should be documented. If ACK loss
and data loss can be detected separately, I think ACK loss rate should
be reported, as it slightly changes the ACK clock (can impact
algorithms like slow start that work on a per ACK basis and can make
the sender more bursty, which could cause more loss).
@ and mine --MM--

3.5 Ancillary metrics relating to the need for advanced TCP features

If TCP would require RFC1323 features (window scaling, timestamp based round trip time measurement, protection from wrapped sequences, etc) to match the BTC performance, it should be reported.

4 Acknowledgments

Jeff Semke, for numerous clarifications.

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