                     Increasing TCP's Initial Window

Abstract

   This document proposes an experiment to increase the permitted TCP
   initial window (IW) from between 2 and 4 segments, as specified in
   RFC 3390, to 10 segments with a fallback to the existing
   recommendation when performance issues are detected. It discusses
   the motivation behind the increase, the advantages and disadvantages
   of the higher initial window, and presents results from several
   large-scale experiments showing that the higher initial window
   improves the overall performance of many web services without
   resulting in a congestion collapse. The document closes with a
   discussion of usage and deployment for further experimental purposes
   recommended by the IETF TCP Maintenance and Minor Extensions (TCPM)
   working group.

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1. Introduction

   This document proposes to raise the upper bound on TCP's initial
   window (IW) to 10 segments (maximum 14600 B). It is patterned after
   and borrows heavily from RFC 3390 [RFC3390] and earlier work in this
   area. Due to lingering concerns about possible side effects to other
   flows sharing the same network bottleneck, some of the
   recommendations are conditional on additional monitoring and
   evaluation.

   The primary argument in favor of raising IW follows from the evolving
   scale of the Internet. Ten segments are likely to fit into queue
   space available at any broadband access link, even when there are a
   reasonable number of concurrent connections.

   Lower speed links can be treated with environment-specific
   configurations, such that they can be protected from being
   overwhelmed by large initial window bursts without imposing a
   suboptimal initial window on the rest of the Internet.

   This document reviews the advantages and disadvantages of using a
   larger initial window and includes summaries of several large-scale
   experiments showing that an initial window of 10 segments (IW10)
   provides benefits across the board for a variety of bandwidth (BW),
   round-trip time (RTT), and bandwidth-delay product (BDP) classes.
   These results show significant benefits for increasing IW for users
   at much smaller data rates than had been previously anticipated.
   However, at initial windows larger than 10, the results are mixed.
   We believe that these mixed results are not intrinsic but are the
   consequence of various implementation artifacts, including overly
   aggressive applications employing many simultaneous connections.

   We recommend that all TCP implementations have a settable TCP IW
   parameter, as long as there is a reasonable effort to monitor for
   possible interactions with other Internet applications and services
   as described in Section 12. Furthermore, Section 10 details why 10
   segments may be an appropriate value, and while that value may
   continue to rise in the future, this document does not include any
   supporting evidence for values of IW larger than 10.

   In addition, we introduce a minor revision to RFC 3390 and RFC 5681
   [RFC5681] to eliminate resetting the initial window when the SYN or
   SYN/ACK is lost.

   The document closes with a discussion of the consensus from the TCPM
   working group on the near-term usage and deployment of IW10 in the
   Internet.

A complementary set of slides for this proposal can be found at
[CD10].

1.1. Terminology

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT",
"SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this
document are to be interpreted as described in RFC 2119 [RFC2119].

2. TCP Modification

This document proposes an increase in the permitted upper bound for
TCP's initial window (IW) to 10 segments, depending on the maximum
segment size (MSS). This increase is optional: a TCP MAY start with
an initial window that is smaller than 10 segments.

More precisely, the upper bound for the initial window will be

$$min (10*MSS, max (2*MSS, 14600)) \tag{1}$$

This upper bound for the initial window size represents a change from
RFC 3390 [RFC3390], which specified that the congestion window be
initialized between 2 and 4 segments, depending on the MSS.

This change applies to the initial window of the connection in the
first round-trip time (RTT) of data transmission during or following
the TCP three-way handshake. Neither the SYN/ACK nor its ACK in the
three-way handshake should increase the initial window size.

Note that all the test results described in this document were based
on the regular Ethernet MTU of 1500 bytes. Future study of the
effect of a different MTU may be needed to fully validate (1) above.

Furthermore, RFC 3390 states (and RFC 5681 [RFC5681] has similar
text):

    If the SYN or SYN/ACK is lost, the initial window used by a sender
    after a correctly transmitted SYN MUST be one segment consisting
    of MSS bytes.

The proposed change to reduce the default retransmission timeout
(RTO) to 1 second [RFC6298] increases the chance for spurious SYN or
SYN/ACK retransmission, thus unnecessarily penalizing connections
with RTT > 1 second if their initial window is reduced to 1 segment.
For this reason, it is RECOMMENDED that implementations refrain from
resetting the initial window to 1 segment, unless there have been
more than one SYN or SYN/ACK retransmissions or true loss detection
has been made.

TCP implementations use slow start in as many as three different
ways: (1) to start a new connection (the initial window); (2) to
restart transmission after a long idle period (the restart window);
and (3) to restart transmission after a retransmit timeout (the loss
window). The change specified in this document affects the value of
the initial window. Optionally, a TCP MAY set the restart window to
the minimum of the value used for the initial window and the current
value of cwnd (in other words, using a larger value for the restart
window should never increase the size of cwnd). These changes do NOT
change the loss window, which must remain 1 segment of MSS bytes (to
permit the lowest possible window size in the case of severe
congestion).

Furthermore, to limit any negative effect that a larger initial
window may have on links with limited bandwidth or buffer space,
implementations SHOULD fall back to RFC 3390 for the restart window
(RW) if any packet loss is detected during either the initial window
or a restart window, and more than 4 KB of data is sent.
Implementations must also follow RFC 6298 [RFC6298] in order to avoid
spurious RTO as described in Section 9.

3. Implementation Issues

The HTTP 1.1 specification allows only two simultaneous connections
per domain, while web browsers open more simultaneous TCP connections
[Ste08], partly to circumvent the small initial window in order to
speed up the loading of web pages as described above.

When web browsers open simultaneous TCP connections to the same
destination, they are working against TCP's congestion control
mechanisms [FF99]. Combining this behavior with larger initial
windows further increases the burstiness and unfairness to other
traffic in the network. If a larger initial window causes harm to
any other flows, then local application tuning will reveal that
having fewer concurrent connections yields better performance for
some users. Any content provider deploying IW10 in conjunction with
content distributed across multiple domains is explicitly encouraged
to perform measurement experiments to detect such problems, and to
consider reducing the number of concurrent connections used to
retrieve their content.

Some implementations advertise a small initial receive window (Table
2 in [Duk10]), effectively limiting how much window a remote host may
use. In order to realize the full benefit of the large initial
window, implementations are encouraged to advertise an initial
receive window of at least 10 segments, except for the circumstances
where a larger initial window is deemed harmful. (See Section 8
below.)

The TCP Selective Acknowledgment (SACK) option [RFC2018] was thought
to be required in order for the larger initial window to perform
well. But measurements from both a testbed and live tests showed that
IW=10 without the SACK option outperforms IW=3 with the SACK option
[CW10].

4. Background

The TCP congestion window was introduced as part of the congestion
control algorithm by Van Jacobson in 1988 [Jac88]. The initial value
of one segment was used as the starting point for newly established
connections to probe the available bandwidth on the network.

Today's Internet is dominated by web traffic running on top of short-
lived TCP connections [IOR2009]. The relatively small initial window
has become a limiting factor for the performance of many web
applications.

The global Internet has continued to grow, both in speed and
penetration. According to the latest report from Akamai [AKAM10],
the global broadband (> 2 Mbps) adoption has surpassed 50%,
propelling the average connection speed to reach 1.7 Mbps, while the
narrowband (< 256 Kbps) usage has dropped to 5%. In contrast, TCP's
initial window has remained 4 KB for a decade [RFC2414],
corresponding to a bandwidth utilization of less than 200 Kbps per
connection, assuming an RTT of 200 ms.

A large proportion of flows on the Internet are short web
transactions over TCP and complete before exiting TCP slow start.
Speeding up the TCP flow startup phase, including circumventing the
initial window limit, has been an area of active research (see
[Sch08] and Section 3.4 of [RFC6077]). Numerous proposals exist
[LAJW07] [RFC4782] [PRAKS02] [PK98]. Some require router support
[RFC4782] [PK98], hence are not practical for the public Internet.
Others suggested bold, but often radical ideas, likely requiring more
years of research before standardization and deployment.

In the mean time, applications have responded to TCP's "slow" start.
Web sites use multiple subdomains [Bel10] to circumvent HTTP 1.1
regulation on two connections per physical host [RFC2616]. As of
today, major web browsers open multiple connections to the same site
(up to six connections per domain [Ste08] and the number is growing).
This trend is to remedy HTTP serialized download to achieve
parallelism and higher performance. But it also implies that today
most access links are severely under-utilized, hence having multiple
TCP connections improves performance most of the time. While raising
the initial congestion window may cause congestion for certain users
of these browsers, we argue that the browsers and other application

need to respect HTTP 1.1 regulation and stop increasing the number of
simultaneous TCP connections. We believe a modest increase of the
initial window will help to stop this trend and provide the best
interim solution to improve overall user performance and reduce the
server, client, and network load.

Note that persistent connections and pipelining are designed to
address some of the above issues with HTTP [RFC2616]. Their presence
does not diminish the need for a larger initial window, e.g., data
from the Chrome browser shows that 35% of HTTP requests are made on
new TCP connections. Our test data also shows significant latency
reduction with the large initial window even in conjunction with
these two HTTP features [Duk10].

Also note that packet pacing has been suggested as a possible
mechanism to avoid large bursts and their associated harm [VH97].
Pacing is not required in this proposal due to a strong preference
for a simple solution. We suspect for packet bursts of a moderate
size, packet pacing will not be necessary. This seems to be
confirmed by our test results.

More discussion of the increase in initial window, including the
choice of 10 segments, can be found in [Duk10] and [CD10].

5. Advantages of Larger Initial Windows

5.1 Reducing Latency

An increase of the initial window from 3 segments to 10 segments
reduces the total transfer time for data sets greater than 4 KB by up
to 4 round trips.

The table below compares the number of round trips between IW=3 and
IW=10 for different transfer sizes, assuming infinite bandwidth, no
packet loss, and the standard delayed ACKs with large delayed-ACK
timer.

```
          ------------------------------------------
         | total segments |   IW=3    |   IW=10    |
          ------------------------------------------
                 3              1            1
                 6              2            1
                10              3            1
                12              3            2
                21              4            2
                25              5            2
                33              5            3
                46              6            3
                51              6            4
                78              7            4
                79              8            4
               120              8            5
               127              9            5
          ------------------------------------------
```

   For example, with the larger initial window, a transfer of 32
   segments of data will require only 2 rather than 5 round trips to
   complete.

5.2. Keeping Up with the Growth of Web Object Size

   RFC 3390 stated that the main motivation for increasing the initial
   window to 4 KB was to speed up connections that only transmit a small
   amount of data, e.g., email and web. The majority of transfers back
   then were less than 4 KB and could be completed in a single RTT
   [All00].

   Since RFC 3390 was published, web objects have gotten significantly
   larger [Chu09] [RJ10]. Today only a small percentage of web objects
   (e.g., 10% of Google's search responses) can fit in the 4 KB initial
   window. The average HTTP response size of gmail.com, a highly
   scripted web site, is 8 KB (Figure 1 in [Duk10]). The average web
   page, including all static and dynamic scripted web objects on the
   page, has seen even greater growth in size [RJ10]. HTTP pipelining
   [RFC2616] and new web transport protocols such as SPDY [SPDY] allow
   multiple web objects to be sent in a single transaction, potentially
   benefiting from an even larger initial window in order to transfer an
   entire web page in a small number of round trips.

5.3. Recovering Faster from Loss on Under-Utilized or Wireless Links

   A greater-than-3-segment initial window increases the chance to
   recover packet loss through Fast Retransmit rather than the lengthy
   initial RTO [RFC5681]. This is because the fast retransmit algorithm
   requires three duplicate ACKs as an indication that a segment has

been lost rather than reordered. While newer loss recovery
techniques such as Limited Transmit [RFC3042] and Early Retransmit
[RFC5827] have been proposed to help speeding up loss recovery from a
smaller window, both algorithms can still benefit from the larger
initial window because of a better chance to receive more ACKs.

6. Disadvantages of Larger Initial Windows for the Individual
    Connection

   The larger bursts from an increase in the initial window may cause
   buffer overrun and packet drop in routers with small buffers, or
   routers experiencing congestion. This could result in unnecessary
   retransmit timeouts. For a large-window connection that is able to
   recover without a retransmit timeout, this could result in an
   unnecessarily early transition from the slow-start to the congestion-
   avoidance phase of the window increase algorithm.

   Premature segment drops are unlikely to occur in uncongested networks
   with sufficient buffering, or in moderately congested networks where
   the congested router uses active queue management (such as Random
   Early Detection [FJ93] [RFC2309] [RFC3150]).

   Insufficient buffering is more likely to exist in the access routers
   connecting slower links. A recent study of access router buffer size
   [DGHS07] reveals the majority of access routers provision enough
   buffer for 130 ms or longer, sufficient to cover a burst of more than
   10 packets at 1 Mbps speed, but possibly not sufficient for browsers
   opening simultaneous connections.

   A testbed study [CW10] on the effect of the larger initial window
   with five simultaneously opened connections revealed that, even with
   limited buffer size on slow links, IW=10 still reduced the total
   latency of web transactions, although at the cost of higher packet
   drop rates as compared to IW=3.

   Some TCP connections will receive better performance with the larger
   initial window, even if the burstiness of the initial window results
   in premature segment drops. This will be true if (1) the TCP
   connection recovers from the segment drop without a retransmit
   timeout, and (2) the TCP connection is ultimately limited to a small
   congestion window by either network congestion or by the receiver's
   advertised window.

7. Disadvantages of Larger Initial Windows for the Network

   An increase in the initial window may increase congestion in a
   network. However, since the increase is one time only (at the
   beginning of a connection), and the rest of TCP's congestion backoff
   mechanism remains in place, it's unlikely the increase by itself will
   render a network in a persistent state of congestion, or even
   congestion collapse. This seems to have been confirmed by the large-
   scale web experiments described later.

   It should be noted that the above may not hold if applications open a
   large number of simultaneous connections.

   Until this proposal is widely deployed, a fairness issue may exist
   between flows adopting a larger initial window vs. flows that are
   compliant with RFC 3390. Although no severe unfairness has been
   detected on all the known tests so far, further study on this topic
   may be warranted.

   Some of the discussions from RFC 3390 are still valid for IW=10.

   Moreover, it is worth noting that although TCP NewReno increases the
   chance of duplicate segments when trying to recover multiple packet
   losses from a large window, the wide support of the TCP Selective
   Acknowledgment (SACK) option [RFC2018] in all major OSes today should
   keep the volume of duplicate segments in check.

   Recent measurements [Get11] provide evidence of extremely large
   queues (in the order of one second or more) at access networks of the
   Internet. While a significant part of the buffer bloat is
   contributed by large downloads/uploads such as video files, emails
   with large attachments, backups and download of movies to disk, some
   of the problem is also caused by web browsing of image-heavy sites
   [Get11]. This queuing delay is generally considered harmful for
   responsiveness of latency-sensitive traffic such as DNS queries,
   Address Resolution Protocol (ARP), DHCP, Voice over IP (VoIP), and
   gaming. IW=10 can exacerbate this problem when doing short
   downloads, such as web browsing [Get11-1]. The mitigations proposed
   for the broader problem of buffer bloating are also applicable in
   this case, such as the use of Explicit Congestion Notification (ECN),
   Active Queue Management (AQM) schemes [CoDel], and traffic
   classification (QoS).

8. Mitigation of Negative Impact

   Much of the negative impact from an increase in the initial window is
   likely to be felt by users behind slow links with limited buffers.
   The negative impact can be mitigated by hosts directly connected to a
   low-speed link advertising an initial receive window smaller than 10
   segments. This can be achieved either through manual configuration
   by the users or through the host stack auto-detecting the low-
   bandwidth links.

   Additional suggestions to improve the end-to-end performance of slow
   links can be found in RFC 3150 [RFC3150].

9. Interactions with the Retransmission Timer

   A large initial window increases the chance of spurious RTO on a low-
   bandwidth path, because the packet transmission time will dominate
   the round-trip time. To minimize spurious retransmissions,
   implementations MUST follow RFC 6298 [RFC6298] to restart the
   retransmission timer with the current value of RTO for each ACK
   received that acknowledges new data.

   For a more detailed discussion, see RFC 3390, Section 6.

10. Experimental Results From Large-Scale Cluster Tests

   In this section, we summarize our findings from large-scale Internet
   experiments with an initial window of 10 segments conducted via
   Google's front-end infrastructure serving a diverse set of
   applications. We present results from two data centers, each chosen
   because of the specific characteristics of subnets served: AvgDC has
   connection bandwidths closer to the worldwide average reported in
   [AKAM10], with a median connection speed of about 1.7 Mbps; SlowDC
   has a larger proportion of traffic from slow-bandwidth subnets with
   nearly 20% of traffic from connections below 100 Kbps; and a third
   was below 256 Kbps.

   Guided by measurements data, we answer two key questions: what is the
   latency benefit when TCP connections start with a higher initial
   window, and on the flip side, what is the cost?

10.1. The Benefits

   The average web search latency improvement over all responses in
   AvgDC is 11.7% (68 ms) and 8.7% (72 ms) in SlowDC. We further
   analyzed the data based on traffic characteristics and subnet
   properties such as bandwidth (BW), round-trip time (RTT), and
   bandwidth-delay product (BDP). The average response latency improved

across the board for a variety of subnets with the largest benefits
of over 20% from high RTT and high BDP networks, wherein most
responses can fit within the pipe. Correspondingly, responses from
low RTT paths experienced the smallest improvements -- about 5%.

Contrary to what we expected, responses from low-bandwidth subnets
experienced the best latency improvements (between 10-20%) in the
0-56 Kbps and 56-256 Kbps buckets. We speculate low-BW networks
observe improved latency for two plausible reasons: 1) fewer slow-
start rounds: unlike many large-BW networks, low-BW subnets with
dial-up modems have inherently large RTTs; and 2) faster loss
recovery: an initial window larger than 3 segments increases the
chances of a lost packet to be recovered through Fast Retransmit as
opposed to a lengthy RTO.

Responses of different sizes benefited to varying degrees; those
larger than 3 segments naturally demonstrated larger improvements,
because they finished in fewer rounds in slow start as compared to
the baseline. In our experiments, response sizes less than or equal
to 3 segments also demonstrated small latency benefits.

To find out how individual subnets performed, we analyzed average
latency at a /24 subnet level (an approximation to a user base that
is offered similar set of services by a common ISP). We find that,
even at the subnet granularity, latency improved at all quantiles
ranging from 5-11%.

10.2. The Cost

To quantify the cost of raising the initial window, we analyzed the
data specifically for subnets with low bandwidth and BDP,
retransmission rates for different kinds of applications, as well as
latency for applications operating with multiple concurrent TCP
connections. From our measurements, we found no evidence of negative
latency impacts that correlate to BW or BDP alone, but in fact both
kinds of subnets demonstrated latency improvements across averages
and quantiles.

As expected, the retransmission rate increased modestly when
operating with larger initial congestion window. The overall
increase in AvgDC is 0.3% (from 1.98% to 2.29%) and in SlowDC is 0.7%
(from 3.54% to 4.21%). In our investigation, with the exception of
one application, the larger window resulted in a retransmission
increase of less than 0.5% for services in the AvgDC. The exception
is the Maps application that operates with multiple concurrent TCP
connections, which increased its retransmission rate by 0.9% in AvgDC
and 1.85% in SlowDC (from 3.94% to 5.79%).

In our experiments, the percentage of traffic experiencing
retransmissions did not increase significantly, e.g., 90% of web
search and maps experienced zero retransmission in SlowDC
(percentages are higher for AvgDC); a break up of retransmissions by
percentiles indicate that most increases come from the portion of
traffic already experiencing retransmissions in the baseline with
initial window of 3 segments.

One of the worst-case scenarios where latency can be adversely
impacted due to bottleneck buffer overflow is represented by traffic
patterns from applications using multiple concurrent TCP connections,
all operating with a large initial window. Our investigation shows
that such a traffic pattern has not been a problem in AvgDC where all
these applications, specifically maps and image thumbnails,
demonstrated improved latencies varying from 2-20%. In the case of
SlowDC, while these applications continued showing a latency
improvement in the mean, their latencies in higher quantiles (96 and
above for maps) indicated instances where latency with larger window
is worse than the baseline, e.g., the 99% latency for maps has
increased by 2.3% (80 ms) when compared to the baseline. There is no
evidence from our measurements that such a cost on latency is a
result of subnet bandwidth alone. Although we have no way of knowing
from our data, we conjecture that the amount of buffering at
bottleneck links plays a key role in the performance of these
applications.

Further details on our experiments and analysis can be found in
[Duk10] and [DCCM10].

11. Other Studies

Besides the large-scale Internet experiments described above, a
number of other studies have been conducted on the effects of IW10 in
various environments. These tests were summarized below, with more
discussion in Appendix A.

A complete list of tests conducted, with their results and related
studies, can be found at the [IW10] link.

1. [Sch08] described an earlier evaluation of various Fast Startup
   approaches, including the "Initial-Start" of 10 MSS.

2. [DCCM10] presented the result from Google's large-scale IW10
   experiments, with a focus on areas with highly multiplexed links
   or limited broadband deployment such as Africa and South America.

3. [CW10] contained a testbed study on IW10 performance over slow
   links. It also studied how short flows with a larger initial
   window might affect the throughput performance of other
   coexisting, long-lived, bulk data transfers.

4. [Sch11] compared IW10 against a number of other fast startup
   schemes, and concluded that IW10 works rather well and is also
   quite fair.

5. [JNDK10] and later [JNDK10-1] studied the effect of IW10 over
   cellular networks.

6. [AERG11] studied the effect of larger sizes of initial congestion
   windows, among other things, on end users' page load time from
   Yahoo!'s Content Delivery Network.

12. Usage and Deployment Recommendations

   Further experiments are required before a larger initial window shall
   be enabled by default in the Internet. The existing measurement
   results indicate that this does not cause significant harm to other
   traffic. However, widespread use in the Internet could reveal issues
   not known yet, e.g., regarding fairness or impact on latency-
   sensitive traffic such as VoIP.

   Therefore, special care is needed when using this experimental TCP
   extension, in particular on large-scale systems originating a
   significant amount of Internet traffic or on large numbers of
   individual consumer-level systems that have similar aggregate impact.
   Anyone (stack vendors, network administrators, etc.) turning on a
   larger initial window SHOULD ensure that the performance is monitored
   before and after that change. Key metrics to monitor are the rate of
   packet losses, ECN marking, and segment retransmissions during the
   initial burst. The sender SHOULD cache such information about
   connection setups using an initial window larger than allowed by RFC
   3390, and new connections SHOULD fall back to the initial window
   allowed by RFC 3390 if there is evidence of performance issues.
   Further experiments are needed on the design of such a cache and
   corresponding heuristics.

   Other relevant metrics that may indicate a need to reduce the IW
   include an increased overall percentage of packet loss or segment
   retransmissions as well as application-level metrics such as reduced
   data transfer completion times or impaired media quality.

   It is important also to take into account hosts that do not implement
   a larger initial window. Furthermore, any deployment of IW10 should
   be aware that there are potential side effects to real-time traffic

(such as VoIP). If users observe any significant deterioration of
performance, they SHOULD fall back to an initial window as allowed by
RFC 3390 for safety reasons. An increased initial window MUST NOT be
turned on by default on systems without such monitoring capabilities.

The IETF TCPM working group is very much interested in further
reports from experiments with this specification and encourages the
publication of such measurement data. By now, there are no adequate
studies available that either prove or do not prove the impact of
IW10 to real-time traffic. Further experimentation in this direction
is encouraged.

If no significant harm is reported, a follow-up document may revisit
the question on whether a larger initial window can be safely used by
default in all Internet hosts. Resolution of these experiments and
tighter specifications of the suggestions here might be grounds for a
future Standards Track document on the same topic.

It is recognized that if IW10 is causing harm to other traffic, that
this may not be readily apparent to the software on the hosts using
IW10. In some cases, a local system or network administrator may be
able to detect this and to selectively disable IW10. In the general
case, however, since the harm may occur on a remote network to other
cross-traffic, there may be no good way at all for this to be
detected or corrected. Current experience and analysis does not
indicate whether this is a real issue, beyond a hypothetical one. As
use of IW10 becomes more prevalent, monitoring and analysis of flows
throughout the network will be needed to assess the impact across the
spectrum of scenarios found on the real Internet.

13. Related Proposals

Two other proposals [All10] [Tou12] have been published to raise
TCP's initial window size over a large timescale. Both aim at
reducing the uncertain impact of a larger initial window at an
Internet-wide scale. Moreover, [Tou12] seeks an algorithm to
automate the adjustment of IW safely over a long period.

Although a modest, static increase of IW to 10 may address the near-
term need for better web performance, much work is needed from the
TCP research community to find a long-term solution to the TCP flow
startup problem.

14. Security Considerations

   This document discusses the initial congestion window permitted for
   TCP connections. Although changing this value may cause more packet
   loss, it is highly unlikely to lead to a persistent state of network
   congestion or even a congestion collapse. Hence, it does not raise
   any known new security issues with TCP.

15. Conclusion

   This document suggests a simple change to TCP that will reduce the
   application latency over short-lived TCP connections or links with
   long RTTs (saving several RTTs during the initial slow-start phase)
   with little or no negative impact over other flows. Extensive tests
   have been conducted through both testbeds and large data centers with
   most results showing improved latency with only a small increase in
   the packet retransmission rate. Based on these results, we believe a
   modest increase of IW to 10 is the best solution for the near-term
   deployment, while scaling IW over the long run remains a challenge
   for the TCP research community.

16. Acknowledgments

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   tests possible. We would especially like to acknowledge Amit
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Appendix A. List of Concerns and Corresponding Test Results

   Concerns have been raised since the initial draft of this document
   was posted, based on a set of large-scale experiments. To better
   understand the impact of a larger initial window and in order to
   confirm or dismiss these concerns, additional tests have been
   conducted using either large-scale clusters, simulations, or real
   testbeds. The following attempts to compile the list of concerns and
   summarize findings from relevant tests.

   o How complete are various tests in covering many different traffic
      patterns?

      The large-scale Internet experiments conducted at Google's front-
      end infrastructure covered a large portfolio of services beyond
      web search. It included Gmail, Google Maps, Photos, News, Sites,
      Images, etc., and covered a wide variety of traffic sizes and
      patterns. One notable exception is YouTube, because we don't
      think the large initial window will have much material impact,
      either positive or negative, on bulk data services.

      [CW10] contains some results from a testbed study on how short
      flows with a larger initial window might affect the throughput
      performance of other coexisting, long-lived, bulk data transfers.

   o Larger bursts from the increase in the initial window cause
      significantly more packet drops.

      All the tests conducted on this subject ([Duk10] [Sch11] [Sch11-1]
      [CW10]) so far have shown only a modest increase of packet drops.
      The only exception is from the testbed study [CW10] under
      extremely high load and/or simultaneous opens. But under those
      conditions, both IW=3 and IW=10 suffered very high packet loss
      rates.

   o A large initial window may severely impact TCP performance over
      highly multiplexed links still common in developing regions.

      Our large-scale experiments described in Section 10 above also
      covered Africa and South America. Measurement data from those
      regions [DCCM10] revealed improved latency, even for those
      services that employ multiple simultaneous connections, at the
      cost of a small increase in the retransmission rate. It seems
      that the round-trip savings from a larger initial window more than
      make up the time spent on recovering more lost packets.

      Similar phenomena have also been observed from the testbed study
      [CW10].

o Why 10 segments?

   Questions have been raised on how the number 10 was picked. We
   have tried different sizes in our large-scale experiments, and
   found that 10 segments seem to give most of the benefits for the
   services we tested while not causing significant increase in the
   retransmission rates. Going forward, 10 segments may turn out to
   be too small when the average of web object sizes continues to
   grow. But a scheme to "right size" the initial window
   automatically over long timescales has yet to be developed.

o More thorough analysis of the impact on slow links is needed.

   Although [Duk10] showed the large initial window reduced the
   average latency even for the dialup link class of only 56 Kbps in
   bandwidth, more studies were needed in order to understand the
   effect of IW10 on slow links at the microscopic level. [CW10] was
   conducted for this purpose.

   Testbeds in [CW10] emulated a 300 ms RTT, bottleneck link
   bandwidth as low as 64 Kbps, and route queue size as low as 40
   packets. A large combination of test parameters were used.
   Almost all tests showed varying degrees of latency improvement
   from IW=10, with only a modest increase in the packet drop rate
   until a very high load was injected. The testbed result was
   consistent with both the large-scale data center experiments
   [CD10] [DCCM10] and a separate study using the Network Simulation
   Cradle (NSC) framework [Sch11] [Sch11-1].

o How will the larger initial window affect flows with initial
   windows of 4 KB or less?

   Flows with the larger initial window will likely grab more
   bandwidth from a bottleneck link when competing against flows with
   smaller initial windows, at least initially. How long will this
   "unfairness" last? Will there be any "capture effect" where flows
   with larger initial window possess a disproportional share of
   bandwidth beyond just a few round trips?

   If there is any "unfairness" issue from flows with different
   initial windows, it did not show up in the large-scale
   experiments, as the average latency for the bucket of all
   responses less than 4 KB did not seem to be affected by the
   presence of many other larger responses employing large initial
   window. As a matter of fact, they seemed to benefit from the
   large initial window too, as shown in Figure 7 of [Duk10].

The same phenomenon seems to exist in the testbed experiments
[CW10]. Flows with IW=3 only suffered slightly when competing
against flows with IW=10 in light to medium loads. Under high
load, both flows' latency improved when mixed together. Also
long-lived, background bulk-data flows seemed to enjoy higher
throughput when running against many foreground short flows of
IW=10 than against short flows of IW=3. One plausible explanation
was that IW=10 enabled short flows to complete sooner, leaving
more room for the long-lived, background flows.

A study using an NSC simulator has also concluded that IW=10 works
rather well and is quite fair against IW=3 [Sch11] [Sch11-1].

o How will a larger initial window perform over cellular networks?

Some simulation studies [JNDK10] [JNDK10-1] have been conducted to
study the effect of a larger initial window on wireless links from
2G to 4G networks (EGDE/HSPA/LTE). The overall result seems mixed
in both raw performance and the fairness index.

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