Congestion Control Working Group
Internet-Draft
Updates: RFC5681, RFC9002, RFC9260, RFC9438 (if approved)
Intended status: Standards Track
Expires: 21 August 2026

M. Welzl
University of Oslo
T. Henderson
University of Washington
G. Fairhurst
University of Aberdeen
M. P. Tahiliani
National Institute of Technology Karnataka

17 February 2026

# Increase of the Congestion Window when the Sender Is Rate-Limited
draft-ietf-ccwg-ratelimited-increase-03

## Abstract

This document specifies how transport protocols increase their congestion window when the sender is rate-limited, and updates RFC 5681, RFC 9002, RFC 9260, and RFC 9438. Such a limitation can be caused by the sending application not supplying data or by receiver flow control.

## About This Document

This note is to be removed before publishing as an RFC.

The latest revision of this draft can be found at https://mwelzl.github.io/draft-ccwg-ratelimited-increase/draft-ietf-ccwg-ratelimited-increase.html. Status information for this document may be found at https://datatracker.ietf.org/doc/draft-ietf-ccwg-ratelimited-increase/.

Discussion of this document takes place on the Congestion Control Working Group Working Group mailing list (mailto:ccwg@ietf.org), which is archived at https://mailarchive.ietf.org/arch/browse/ccwg/. Subscribe at https://www.ietf.org/mailman/listinfo/ccwg/.

Source for this draft and an issue tracker can be found at https://github.com/mwelzl/draft-ccwg-ratelimited-increase.

## Status of This Memo

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

This Internet-Draft will expire on 21 August 2026.

## Copyright Notice



## Table of Contents

## 1. Introduction

A sender of a congestion controlled transport protocol becomes "rate-limited" when it does not send any data even though the congestion control rules would allow it to transmit data. This could occur because the application has not provided sufficient data to fully utilise the congestion window (cwnd). It could also occur because the receiver has limited the sender using flow control (e.g., by the advertised TCP receiver window (rwnd) or by the connection or stream flow credit in QUIC). Current RFCs specifying congestion control algorithms diverge regarding the rules for increasing the cwnd when the sender is rate-limited.

Congestion Window Validation (CWV) [RFC7661] provides an experimental specification defining how to manage a cwnd that has become larger than the current flight size, and how to respond to detected congestion when this is the case. In contrast, this present document concerns the increase in cwnd when a sender is rate-limited. These two topics are distinct, but are related, because both describe the management of the cwnd when a sender does not fully utilise the current cwnd.

An appendix provides an example of how rate-limited increase can play out.

RFC-Ed Note, please remove the following sentence prior to publication: Another appendix provides an overview of the divergence in current RFCs and some implementations regarding cwnd increase when the sender is rate-limited (the second appendix is to be removed before publication).

## 2. Conventions and Definitions

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

### 2.1. Terminology

This document uses the terms defined in Section 2 of [RFC5681] and Section 3 of [RFC7661]. Additionally, we define:

* initcwnd: The initial value of the congestion window, also known as the "initial window" ("IW" in [RFC5681]).

* maxFS: the largest value of FlightSize since the last time that cwnd was decreased. If cwnd has never been decreased, maxFS is the maximum value of FlightSize since the start of the data transfer, and at least as large as initcwnd.

## 3. Rate-Limited Increase

When FlightSize < cwnd, regardless of the current state of a congestion control algorithm, the following "Rate-Limited Increase" rules apply for senders using a congestion controlled transport protocol:

The sender MUST initialise the maxFS parameter to initcwnd when the congestion control algorithm is started. Thereafter when the FlightSize is updated, the sender updates maxFS:

```
maxFS = max(FlightSize, maxFS)
```

Upon a reduction of cwnd (for any reason), maxFS MUST be reset to zero. This ensures that maxFS is reinitialized using the first FlightSize measurement taken after the cwnd reduction.

The sender MUST cap cwnd to be no larger than limit(maxFS).

The function limit() returns the maximum cwnd value the congestion control algorithm would yield by increasing for all ACKs that would be produced by successfully transmitting one window of size maxFS. For example, for Slow Start, as specified in [RFC5681], limit(maxFS)=2*maxFS, such that equation 2 in [RFC5681] becomes:

```
cwnd_new = cwnd + min (N, SMSS)
cwnd = min(cwnd_new, 2*maxFS)
```

where cwnd and SMSS follow their definitions in [RFC5681] and N is the number of previously unacknowledged bytes acknowledged in the incoming ACK.

Similarly, with Rate-Limited Increase applied in Congestion Avoidance, limit(maxFS)=SMSS+maxFS, such that equation 3 in [RFC5681] becomes:

```
cwnd_new = cwnd + SMSS*SMSS/cwnd
cwnd = min(cwnd_new, SMSS+maxFS)
```

where cwnd and SMSS follow their definitions in [RFC5681].

NOTE: This specification defines the current method used to increase the cwnd for a rate-limited sender. Without a way to reduce cwnd when the transport sender becomes rate-limited, maxFS can stay valid for a long time, possibly not reflecting the reality of the end-to-end Internet path in use. This is remedied by "Congestion Window Validation" in [RFC7661], which also defines a "pipeACK" variable that measures the recently acknowledged size of the network pipe when the sender was rate-limited.

### 3.1. Example

We illustrate the working of Rate-Limited Increase by showing the increase of cwnd in two scenarios: when the growth of cwnd is unconstrained, and when the rate-limited sender is constrained by Rate-Limited Increase. For simplicity, this example accounts for the cwnd in segments, rather than bytes. In both cases, we assume the initial cwnd (initcwnd) = 10 segments, as defined for TCP in [RFC6928] and QUIC in [RFC9002], a single connection begins with Slow Start, the sender transmits a total of 14 segments but pauses after transmitting 10 segments and resumes the transmission for the remaining 4 segments afterwards, no packets are lost, and an ACK is sent for every packet.

#### 3.1.1. Unconstrained sender

Initially, cwnd = initcwnd. Therefore, using initcwnd = 10 segments, the sender transmits 10 segments and pauses. Since the sender is in the Slow Start phase, the arrival of an each ACK for the 10 sent segments increases the cwnd by 1 segment, resulting in the cwnd increasing to 20 segments. Subsequently, after the pause, the sender transmits 4 segments and pauses again. As a consequence, the arrival of 4 ACKs results in cwnd further increasing to 24 segments, even though the sender is rate-limited (i.e., has never sent more than 10 segments per round-trip time (RTT)).

#### 3.1.2. Sender constrained by Rate-Limited Increase

Initially, cwnd = initcwnd. Therefore, using initcwnd = 10 segments, the sender transmits 10 segments and pauses; note that FlightSize and maxFS are both 10 segments at this point. Since the sender is in the Slow Start phase, the arrival of each ACK for the 10 sent segments increases the cwnd by 1 segment, resulting in the cwnd increasing to 20 segments. Subsequently, when the sender resumes and transmits 4 new segments, Rate-Limited Increase constrains the growth of the cwnd because FlightSize < cwnd and therefore this caps the cwnd to be no larger than limit(maxFS) = 2 X maxFS = 2 X 10 segments = 20 segments.

### 3.2. Discussion

If the sending rate is less than the rate permitted by the cwnd for multiple RTTs, limited either by the sending application or by the receiver-advertised window, a continuous increase in the cwnd would cause a mismatch between the cwnd and the capacity that the path supports (i.e., over-estimating the capacity). Such unlimited growth in the cwnd is therefore disallowed.

However, in most common congestion control algorithms, in the absence of an indication of congestion, a cwnd that has been fully utilized during an RTT (where a sender was cwnd-limited) permits the cwnd to be increased during the immediately following RTT. This increase is allowed by Rate-Limited Increase.

#### 3.2.1. Rate-based congestion control

The present document updates congestion control specifications that use a cwnd to limit the number of unacknowledged bytes (or packets) that a sender is allowed to emit. Use of a cwnd variable to control sending rate is not the only mechanism available and not the only mechanism that is used in practice.

Congestion control algorithms can also constrain data transmission by explicitly calculating the sending rate over some time interval, by "pacing" packets (injecting pauses in between their transmission) or via combinations of the above (e.g., BBR combines these three methods [I-D.ietf-ccwg-bbr]). The guiding principle behind Rate-Limited Increase applies to all congestion control algorithms: in the absence of a congestion indication, a sender is allowed to increase its rate from the amount of data that it has transmitted during the previous RTT (this holds irrespective of whether the sender is rate-limited or not). Therefore, congestion control algorithms SHOULD implement a behavior that is equivalent to Rate-Limited Increase, irrespective of whether they use a cwnd variable or not.

#### 3.2.2. Pacing

Pacing mechanisms seek to avoid the negative impacts associated with "bursts" (flights of packets transmitted back-to-back). Rate-Limited Increase introduces a limit using "maxFS", which is based on the number of bytes in flight during a previous RTT; thus, as long as the number of bytes in flight per RTT is unaffected by pacing, Rate-Limited Increase does not constrain the use of pacing mechanisms.

## 4. Security Considerations

While congestion control designs could result in unwanted competing traffic, they do not directly result in new security considerations.

The security considerations are the same as for other congestion control methods. Such methods rely on the receiver appropriately acknowledging receipt of data. The ability of an on-path or off-path attacker to influence congestion control depends upon the security properties of the transport protocol being used. Transport protocols that provide authentication (including those using encryption), or are carried over protocols that provide authentication, can protect their congestion control algorithm from network attack. This is orthogonal to the specification of congestion control rules.

## 5. IANA Considerations

This document requests no IANA action.

## 6. References

### 6.1. Normative References

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## 6.2. Informative References

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[RFC4341] Floyd, S. and E. Kohler, "Profile for Datagram Congestion Control Protocol (DCCP) Congestion Control ID 2: TCP-like Congestion Control", RFC 4341, DOI 10.17487/RFC4341, March 2006, <https://www.rfc-editor.org/rfc/rfc4341>.

[RFC6928] Chu, J., Dukkipati, N., Cheng, Y., and M. Mathis, "Increasing TCP's Initial Window", RFC 6928, DOI 10.17487/RFC6928, April 2013, <https://www.rfc-editor.org/rfc/rfc6928>.

# Appendix A. An Example Using cwnd Represented in Bytes

The following informative example is provided for a sender that maintains the cwnd in bytes. 36 packets are sent in this example over four rounds of transmission. This shows the initial growth of the cwnd by a rate-limited sender, followed by a transmission that uses the full available cwnd.

The initial sender state is:

Sender sequence number (seqno) = 0
MSS = 1000 bytes
cwnd = 10000 bytes (initcwnd)
maxFS = 10000 bytes (initcwnd)
FlightSize (FS) = 0 bytes
ssthresh is infinity, i.e. the congestion control algorithm is in slow start.

The network path窶冱 bandwidth-delay product is such that, throughout this example, all packets in each round are sent before an ACK is received for the first packet in a round. One ACK is generated for each 2*MSS received bytes.

Round 1, the sender has 4000B to send in 4 packets: MSS=1000, cwnd=10000

Send seqno=0; FS=1000; maxFS=10000
Send seqno=1000; FS=1000; maxFS=10000
Send seqno=2000; FS=2000; maxFS=10000
Send seqno=3000; FS=3000; maxFS=10000

Received 2 ACKs; maxFS=10000, if (cwnd<2*maxFS) {cwnd +=ACK窶冊d}

ACK for 2000 ACK窶冊d=2000 : cwnd+= 2000; cwnd=12000
ACK for 4000 ACK窶冊d=2000 : cwnd+= 2000; cwnd=14000

Note: This round maxFS was not increased and cwnd was increased.

Round 2, the sender has 8000B to send in 8 packets: MSS=1000, cwnd=14000

Send seqno=4000; FS=1000; maxFS=10000
Send seqno=5000; FS=2000; maxFS=10000
Send seqno=6000; FS=3000; maxFS=10000
Send seqno=7000; FS=4000; maxFS=10000
Send seqno=8000; FS=5000; maxFS=10000
Send seqno=9000; FS=6000; maxFS=10000
Send seqno=10000; FS=7000; maxFS=10000
Send seqno=11000; FS=8000; maxFS=10000

Received 4 ACKs; maxFS=10000, if (cwnd<2*maxFS) {cwnd +=ACK窶冊d}

ACK for 6000 ACK窶冊d=2000 : cwnd+=2000; cwnd=16000
ACK for 8000 ACK窶冊d=2000 : cwnd+=2000; cwnd=18000
ACK for 10000 ACK窶冊d=2000 : cwnd+=2000; cwnd=20000
ACK for 12000 ACK窶冊d=2000 : cwnd+=0; cwnd=20000

Note: This round maxFS was not increased and cwnd was increased to 2*maxFS.

Round 3, the sender has 4000B to send in 4 packets: MSS=1000, cwnd=20000

Send seqno=12000; FS=1000; maxFS=10000
Send seqno=13000; FS=2000; maxFS=10000
Send seqno=14000; FS=3000; maxFS=10000
Send seqno=15000; FS=4000; maxFS=10000

Received 2 ACKs; maxFS=10000, if (cwnd<2*maxFS) {cwnd +=ACK窶册d}

ACK for 14000 ACK窶册d=2000 : cwnd+=0; cwnd=20000
ACK for 16000 ACK窶册d=2000 : cwnd+=0; cwnd=20000

Note: This round maxFS was not increased and cwnd was not increased.

Round 4, the sender has 20000B to send in 20 packets: MSS=1000, cwnd=20000

Send seqno=16000; FS= 1000; maxFS=10000
Send seqno=17000; FS= 2000; maxFS=10000
Send seqno=18000; FS= 3000; maxFS=10000
Send seqno=19000; FS= 4000; maxFS=10000
Send seqno=20000; FS= 5000; maxFS=10000
Send seqno=21000; FS= 6000; maxFS=10000
Send seqno=22000; FS= 7000; maxFS=10000
Send seqno=23000; FS= 8000; maxFS=10000
Send seqno=24000; FS= 9000; maxFS=10000
Send seqno=25000; FS=10000; maxFS=10000
Send seqno=26000; FS=11000; maxFS=11000
Send seqno=27000; FS=12000; maxFS=12000
Send seqno=28000; FS=13000; maxFS=13000
Send seqno=29000; FS=14000; maxFS=14000
Send seqno=30000; FS=15000; maxFS=15000
Send seqno=31000; FS=16000; maxFS=16000
Send seqno=32000; FS=17000; maxFS=17000
Send seqno=33000; FS=18000; maxFS=18000
Send seqno=34000; FS=19000; maxFS=19000
Send seqno=35000; FS=20000; maxFS=20000

Received 10 ACKs; maxFS=20000, if (cwnd<2*maxFS) {cwnd +=ACK窶册d}

```
  ACK for 18000 ACK窶册d=2000 : cwnd+=2000; cwnd=22000
  ACK for 20000 ACK窶册d=2000 : cwnd+=2000; cwnd=24000
  ACK for 22000 ACK窶册d=2000 : cwnd+=2000; cwnd=26000
  ACK for 24000 ACK窶册d=2000 : cwnd+=2000; cwnd=28000
  ACK for 26000 ACK窶册d=2000 : cwnd+=2000; cwnd=30000
  ACK for 28000 ACK窶册d=2000 : cwnd+=2000; cwnd=32000
  ACK for 30000 ACK窶册d=2000 : cwnd+=2000; cwnd=34000
  ACK for 32000 ACK窶册d=2000 : cwnd+=2000; cwnd=36000
  ACK for 34000 ACK窶册d=2000 : cwnd+=2000; cwnd=38000
  ACK for 36000 ACK窶册d=2000 : cwnd+=2000; cwnd=40000
```

Note: In this round, maxFS was increased and cwnd was increased to 2*maxFS.

# Appendix B. The state of RFCs and implementations

RFC-Ed Note: This section is provided as input for IETF discussion, and should be removed before publication.

## B.1. TCP ("Reno" congestion control)

### B.1.1. Specification

[RFC7661] suggests there is no increase limitation in the standard TCP behavior (which [RFC7661] changes), on page 4:

> Standard TCP does not impose additional restrictions on the growth of the congestion window when a TCP sender is unable to send at the maximum rate allowed by the cwnd. In this case, the rate-limited sender may grow a cwnd far beyond that corresponding to the current transmit rate, resulting in a value that does not reflect current information about the state of the network path the flow is using.

### B.1.2. Implementation

* ns-2 allows cwnd to grow when it is rate-limited by rwnd. (Rate-limited by the sending application: not tested.)

* Until release 3.42, ns-3 allowed cwnd to grow when rate-limited, either due to an application or rwnd limit. Since release 3.42, ns-3 TCP models conform to Rate-Limited Increase, following the current Linux TCP approach in this regard (see next bullet).

* In Congestion Avoidance, Linux only allows the cwnd to grow when the sender is unconstrained. Before kernel version 3.16, this also applied to Slow Start. The check for "unconstrained" is perfomed by checking if FlightSize is greater or equal to cwnd.

> Since kernel version 3.16, which was published in August 2014, in Slow Start, the increase implements Rate-Limited Increase in the tcp_is_cwnd_limited function in tcp.h.

#### B.1.3. Assessment

Linux implements a limit to cwnd growth in accordance with Rate-Limited Increase; in Slow Start, this limit follows the rule's upper limit, while in Congestion Avoidance, it is more conservative than Rate-Limited Increase. The specification and the ns-2 and (older) ns-3 implementations are in conflict with Rate-Limited Increase.

### B.2. CUBIC

#### B.2.1. Specification

Section 5.8 of [RFC9438] says:

> Cubic doesn't increase cwnd when it's limited by the sending application or rwnd.

#### B.2.2. Implementation

The description of Linux described in Appendix B.1.2 also applies to Cubic.

#### B.2.3. Assessment

Both the specification and the Linux implementation limit the cwnd growth in accordance with Rate-Limited Increase; in Congestion Avoidance, this limit is more conservative than Rate-Limited Increase, and in Slow Start, it implements the "maxFS" upper limit of Rate-Limited Increase.

### B.3. The Stream Control Transmission Protocol (SCTP)

#### B.3.1. Specification

Section 7.2.1 of [RFC9260] says:

> When cwnd is less than or equal to ssthresh, an SCTP endpoint MUST use the slow-start algorithm to increase cwnd only if the current congestion window is being fully utilized and the data sender is not in Fast Recovery. Only when these two conditions are met can the cwnd be increased; otherwise, the cwnd MUST NOT be increased.

#### B.3.2. Assessment

The quoted statement from [RFC9260] prescribes the same cwnd growth limitation that is also specified for Cubic and implemented for both Reno and Cubic in Linux. It is in accordance with Rate-Limited Increase, and more conservative.

Section 7.2.1 of [RFC9260] is specifically limited to Slow Start. Congestion Avoidance is discussed in Section 7.2.2 of [RFC9260] However, this section neither contains a similar rule, nor does it refer back to the rule that limits the growth of cwnd in Section 7.2.1. It is thus implicitly clear that the quoted rule only applies to Slow Start, whereas Rate-Limited Increase applies to both Slow Start and Congestion Avoidance.

### B.4. The QUIC Transport Protocol

#### B.4.1. Specification

Section 7.8 of [RFC9002] states:

> When bytes in flight is smaller than the congestion window and sending is not pacing limited, the congestion window is underutilized. This can happen due to insufficient application data or flow control limits. When this occurs, the congestion window SHOULD NOT be increased in either slow start or congestion avoidance.

#### B.4.2. Assessment

With the exception of pacing, this specification conservatively limits the growth in cwnd, similar to Cubic and SCTP. It is in accordance with Rate-Limited Increase, and more conservative.

### B.5. The Datagram Congestion Control Protocol (DCCP) CCID2

#### B.5.1. Specification

Section 5.1 of [RFC4341] states: >There are currently no standards governing TCP’s use of the congestion window during an application-limited period. In particular, it is possible for TCP’s congestion window to grow quite large during a long uncongested period when the sender is application limited, sending at a low rate. [RFC2861] essentially suggests that TCP’s congestion window not be increased during application-limited periods when the congestion window is not being fully utilized.

### B.5.2. Assessment

A DCCP Congestion Control ID (CCID) specifing TCP-like behaviour ought to follow the method specified in this document. The current guidance relates only to [RFC2861]. The text in Section 5.1 of [RFC4341] is updated by this document to specify the management of the cwnd when the sender is rate-limited.

## Appendix C. Change Log

* -00 was the first individual submission for feedback by CCWG.

* -01 includes editorial improvements

  - Removes application interaction with QUIC pacing, since pacing might be within the QUIC stack.

  - Adds explicit mention of DCCP/CCID2.

  - Adds this change log.

* -02 addresses comments from IETF-119

  - Discusses rate-based controls and pacing.

  - Trims the list of possible RFCs to update.

  - Some editorial fixes: "congestion control algorithm" instead of "mechanism" for consistency with RFC5033.bis; earlier definition of maxFS; explicit mention of RFCs to update in abstract.

* -03 addresses comments from IETF-120

  - Introduces a third rule, with MAY, that avoids having an unvalidated long-lived maxFS (using pipeACK from RFC 7661).

  - Changes "inc" to "limit" and adapts the wording of rule 2 to make it clearer (thanks to Neal Cardwell).

  - Appendix: updates ns-3 in line with the recent implementation.

  - Appendix: makes the RFC 9002 text clearer and shorter.

* draft-ietf-ccwg-ratelimited-increase-00

  - adds Mohit Tahiliani as a co-author

- refines the "rule" text (shorter, clearer)
- adds an example

* draft-ietf-ccwg-ratelimited-increase-01
  - Clarified what we mean with an RTT
  - rephrased example regarding initcwnd, citing RFCs 6928 and 9002
  - removed the too vague rule 1 and made rule 2 (now rule 1) a MUST

* draft-ietf-ccwg-ratelimited-increase-02
  - Improved the last sentence of section 3.1.2.
  - Removed a confusing and unnecessary sentence about pacing (as suggested at IETF-123).

* draft-ietf-ccwg-ratelimited-increase-03
  - The editors checked rule 2, and found that rule 1 was sufficient, and did not depend on the ordering of rules in newCWV (RFC7661), hence rule 2 was finally removed.
  - Cleaned language and improved text explaining how this compliments RFC7661.
  - Checked/updated definitions.
  - Added an example with cwnd in bytes.

## Acknowledgments

The authors would like to thank Neal Cardwell and Martin Duke for suggesting improvements to this document.

## Authors' Addresses

Michael Welzl
University of Oslo
PO Box 1080 Blindern
0316 Oslo
Norway
Email: michawe@ifi.uio.no
URI: http://welzl.at/

Tom Henderson
University of Washington
185 Stevens Way
Seattle, WA 98195,
United States
Email: tomh@tomh.org
URI: https://www.tomh.org/

Godred Fairhurst
University of Aberdeen
Fraser Noble Building
Aberdeen, AB24 3UE
United Kingdom
Email: gorry@erg.abdn.ac.uk
URI: https://www.erg.abdn.ac.uk/

Mohit P. Tahiliani
National Institute of Technology Karnataka
P. O. Srinivasnagar, Surathkal
Mangalore, Karnataka - 575025
India
Email: tahiliani@nitk.edu.in
URI: https://tahiliani.in/