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Congestion Control in the RFC Series
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Abstract

This document is a survey of congestion control topics within the RFC series. The intent of this document is to be an informational snapshot of the current state of Internet standards and other IETF products related to congestion control. This is an initial product of the IRTF's Internet Congestion Control Research Group and may be used as one reference or starting point for the future work of the research group.

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1. Introduction

In this document, we define congestion control as the feedback-based adjustment of the rate at which data is sent into the network. Congestion control is an indispensable set of principles and mechanisms for maintaining the stability of the Internet. Congestion control has been closely associated with TCP since Van Jacobson's work in 1988 [[Jac88](#)], but there has also been a great deal of congestion control work outside of TCP (e.g. for real-time multimedia applications, multicast, and router-based mechanisms). Several such proposals have been produced within the IETF and published as RFCs, along with RFCs that give architectural guidance (e.g. by pointing out the importance of performing some form of congestion control). Several of these mechanisms are in use within the Internet.

When designing a new Internet protocol, it is therefore important to not only understand how congestion control works in TCP but also have a broader understanding of congestion control and know about other related RFCs -- some of them give guidance, some of them describe mechanisms which may have a direct influence on a newly designed protocol, and some of them may only be "related work" worth knowing about. The purpose of this document is to facilitate and encourage this search for knowledge by providing an overview of RFCs related to congestion control that have been published thus far. This document is a product of the IRTF's Internet Congestion Control Research Group (ICCRG) as a strong grasp of the existing literature should benefit further ICCRG work. The format of this document is similar to an annotated bibliography. Although host and router requirements for congestion control functions are discussed, this is only an informational document and does not contain any formal standards bearing of its own.

Congestion control is a large and active topic, and so the scope of this document is limited to published RFCs and a small number of current working group drafts. This allows the document to focus on congestion control principles and mechanisms that in some sense are

more well-known, well-accepted, or widely-used. Significant contributions to this subject also exist in both the academic literature and in the form of individual submission Internet-drafts, however we exclude these from this study. In many cases the RFC describing some mechanism will contain references to relevant academic publications in journals or conference proceedings that presented the research and validation of the mechanism. For instance, [RFC 2581](#) cites Jacobson's 1988 SIGCOMM paper that has a less standards-oriented but more illustrative treatment and explanation of some of the mechanisms in [RFC 2581](#).

The majority of the documents discussed here pertain to end-host

based congestion control. Many network-based mechanisms, such as a number of queue management algorithms, do not require any protocol exchanges between elements, but merely operate within a single host. Thus, network-based congestion control mechanisms have often not been described in any RFC, as they generally fall under the domain of implementation details that do not influence interoperability.

We specifically do not include the vast amount of quality of service (QoS) work into the scope of this document, as it is a full field in its own right, and deals with issues that are mostly orthogonal to end-host congestion control and router queue management. Scheduling mechanisms used to implement QoS (on either per-flow or an aggregate basis), for instance, can be used independently of the end-host congestion control and queue management functions also in use. Similar arguments can be made for traffic-shaping, admission control, and other functions that are topical to QoS, and only side-notes for congestion control.

To organize the subject matter in this document, the content is classified into several broad categories. First, we list documents relating to Internet architecture and general architectural concepts in [Section 2](#). Next, the congestion control algorithms used in the TCP transport protocol are discussed in [Section 3](#). Discussion of the interactions between link properties and mechanisms with the kinds of algorithms and heuristics used within TCP congestion control is contained in [Section 4](#). One method that has been developed by the IETF (and deployed to some extent) for allowing network-based and host-based congestion control to interact without dropping packets is the subject of [Section 5](#). The congestion control algorithms used by

unicast transport protocols other than TCP are described in [Section 6](#). Work that has been done on congestion control for multicast transports and applications is listed in [Section 7](#). Finally, documents that have historic significance, but perhaps not current direct technical application have been classified into [Section 8](#).

[2](#). Architectural Documents

Some documents in this section contain architectural guidance and concerns, while others specify congestion control related mechanisms which are broadly applicability and have impacts on more than a single class of traffic as per our classification. Some of these documents are direct products of the IAB, giving their thoughts on specific aspects of congestion control in the Internet.

[RFC 1958](#): "Architectural Principles of the Internet" (June 1996)

Several guidelines for network systems design that have proven useful in the evolution of the Internet are sketched in this document. Congestion control is not specifically mentioned or alluded to, but the general principles apply to congestion control. For instance, performing end-to-end functions at end nodes, lack of centralized control, heterogeneity, scalability, simplicity, avoiding options and parameters, etc. are all valid concerns in the design and assessment of congestion control schemes for the Internet.

[RFC 2309](#): "Recommendations on Queue Management and Congestion Avoidance in the Internet" (April 1998)

This document briefly discusses the history of congestion and the origin of congestion control in the Internet. The focus is mainly on network- or router-based queue management algorithms. This RFC recommends to test, standardize and deploy Active Queue Management (AQM) in routers; it provides an overview of one such mechanism, Random Early Detection (RED) and explains how and why AQM mechanisms can improve the performance of the Internet. Finally, this document explains the danger of a possible "congestion collapse" from unresponsive flows and makes a strong recommendation to develop and eventually deploy router mechanisms to protect the Internet from such traffic.

[RFC 2914](#): "Congestion Control Principles" (September 2000)

This document is a general discussion of the principles of congestion control. It points out that there are an increasing number of applications which do not use TCP, and elaborates on the importance of carrying out congestion control for such traffic in order to prevent congestion collapse. The TCP Reno congestion control mechanisms are described as an example of end-to-end congestion control within transport protocols.

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Congestion Control RFCs

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[RFC 3124](#): "The Congestion Manager" (June 2001)

This document specifies the Congestion Manager, an end-system module that realizes congestion control on a per-host rather than a per-connection basis, which may be a more appropriate way to carry out congestion control. Using the Congestion Manager, multiple streams between two hosts (which may include TCP flows) can easily adapt to network congestion in a unified fashion.

[RFC 3426](#): "General Architectural and Policy Considerations" (November 2002) [RFC 3426](#) lists a number of questions that can be answered for a particular technical solution in order to determine its architectural impact and desirability. These are highly valid for congestion control mechanisms, and end-point congestion management

is used as an example case-study several times in [RFC 3426](#).

[RFC 3439](#): "Some Internet Architectural Guidelines and Philosophy" (December 2002)

Primarily focused on the design of Internet "backbone" networks, this document supplements [RFC 1958](#). Simplicity is stressed, as the unpredictable results of complexity (due to amplification and coupling) are described. Congestion control issues stemming from layering interactions between transport and lower protocols are presented, as well as other items relevant to congestion control, including asymmetry and the "myth of over-provisioning".

[RFC 3714](#): "IAB Concerns Regarding Congestion Control for Voice Traffic in the Internet" (March 2004)

This document expresses the IAB's concern over the lack of effective end-to-end congestion control for best-effort voice traffic, which is noted as currently being an available service with growing demand. An example of a VoIP connection between Atlanta, Georgia, USA, and Nairobi, Kenya, is given, where a single VoIP call consumed more than half of the access link capacity (which is normally shared across several different users). This example is used as the basis for further discussion, making it clear that using some form of congestion control for VoIP traffic is highly recommended.

[3.](#) TCP Congestion Control

Basic TCP congestion control is defined in [RFC 2581](#), with many other RFCs that specify ancillary modifications and enhancements. The reader may refer to the TCP Roadmap [[RFC4614](#)] for more information on this subject.

Recently, significant effort has been put into experimental TCP

congestion control modifications for obtaining high throughput with reduced startup and recovery times. RFCs have been published on some of these modifications, including HighSpeed TCP, and Limited Slow-Start. Other schemes, such as H-TCP, have been published as Internet-Drafts and been discussed by the IETF, but much of the work in this area has not been brought to the IETF (e.g. FAST, BIC/CUBIC, Scalable TCP, and others), so the majority of this work is outside the RFC series and will be discussed in other products of the ICCRG.

Congestion control mechanisms adjust the sending rate on the basis of feedback that would reflect the state of the path between the sender and the receiver. Such feedback can take many forms, binary or with a finer granularity, implicit as well as explicit. TCP, SCTP and DCCP make use of implicit feedback -- packet loss, which is commonly interpreted as a sign of congestion, and RTT measurements -- which can lead to adverse interactions with certain links. Other link characteristics (such as a large bandwidth*delay product) are challenging for congestion control mechanisms because they tend to magnify any problems that such mechanisms may have. The documents in these section discuss challenging link characteristics; many of them were written by the "Performance Implications of Link Characteristics" (PILC) Working Group.

While these documents often refer to specific problems with TCP, the link characteristics that they describe can be expected to affect other congestion control mechanisms too. In particular, any interactions between special links and TCP congestion control will be similar for protocols that use the same congestion control behavior, such as SCTP and DCCP with CCID 2 (see [Section 6](#)), and should be taken into consideration by designers of congestion control mechanisms which utilize the same kind of feedback as TCP.

Some RFCs only make recommendations regarding the implementation and configuration of TCP based upon characteristics of special links. As these RFCs are so closely connected to the specification of TCP itself, they are not included in this document.

[RFC 3135](#): "Performance Enhancing Proxies Intended to Mitigate Link-Related Degradations" (June 2001)

This document is a survey of Performance Enhancing Proxies (PEPs) often employed to improve degraded TCP performance caused by characteristics of specific link environments, for example, in satellite, wireless WAN, and wireless LAN environments. Different types of Performance Enhancing Proxies are described as well as the mechanisms used to improve performance. While there is a specific focus on TCP in this document, PEPs can operate on any protocol, and the performance enhancements that PEPs achieve are often closely related to congestion control.

[RFC 3150](#): "End-to-end Performance Implications of Slow Links" (July 2001)

This document makes performance-related recommendations for users

of network paths that traverse "very low bit-rate" links. It includes a discussion of interactions between such links and TCP congestion control.

[RFC 3366](#): "Advice to link designers on link Automatic Repeat reQuest (ARQ)" (August 2002)

Link-layer ARQ techniques are a popular means to increase the robustness of a particular links to transmission errors. As this RFC explains, ARQ techniques on a link can interact poorly with TCP's end-to-end congestion control if they lead to additional delay variation or reordering. This RFC gives some advice on limiting the extent of these types of problematic interactions.

[RFC 3449](#): "TCP Performance Implications of Network Path Asymmetry" (December 2002)

This document describes performance limitations of TCP when the capacity of the ACK path is limited. Several techniques to aid TCP in these circumstances are discussed, particularly ACK congestion control and sender pacing are relevant to other non-TCP congestion control schemes. For instance, in the design of the RMT protocols for multicast, preventing ACK-implosion at multicast sources can be seen as a form of ACK congestion control.

[RFC 3819](#): "Advice for Internet Subnetwork Designers" (July 2004)

Several challenging characteristics in link design and optimization for carrying IP traffic are discussed in this document. The emphasis is mostly on designs that will behave well with TCP running over them, however, most of these principles apply to other transport-layer congestion control techniques as well.

5. Explicit Congestion Notification

There are two bits in the IP header which enable an Active Queue Management mechanism (see [[RFC2309](#)] or [Section 2](#)) to explicitly convey the information "there was congestion" to endpoints when it would normally drop a packet. This mechanism, which is called "Explicit Congestion Notification" (ECN), can therefore reduce the loss experienced by a transport endpoint in the presence of Active Queue Management. While Explicit Congestion Notification is most frequently discussed in the context of TCP (and therefore included in the TCP Roadmap [[RFC4614](#)]), its applicability is broader, and ECN use has also been specified for protocols such as DCCP and SCTP.

[RFC 2481](#): "A Proposal to add Explicit Congestion Notification (ECN) to IP" (January 1999)

This document introduces ECN, describing when the Congestion Experienced (CE) bit in the IP header would be set in routers, and what modifications would be needed to TCP to make it ECN-capable. It includes a discussion of issues related to non-compliant behavior in end nodes and inside the network, IPsec tunnels and dropped or corrupted packets as well as a summary of related work.

[RFC 2884](#): "Performance Evaluation of Explicit Congestion Notification (ECN) in IP Networks" (July 2000)

This document presents a performance study of ECN as specified in [[RFC2481](#)] using an implementation on the Linux Operating System. The experiments focused on ECN for both bulk and transactional transfers, showing that there is improvement in throughput over TCP without ECN in the case of bulk transfers and substantial improvement for transactional transfers.

[RFC 3168](#): "The Addition of Explicit Congestion Notification (ECN) to IP" (September 2001)

This document, which obsoletes [[RFC2481](#)], specifies the

incorporation of ECN into TCP and IP. One notable change in this significantly extended specification is the definition of a bit combination that was not defined in [[RFC2481](#)], which can be used to realize a nonce that would prevent a receiver from falsely claiming that there was no congestion. Potential issues related to ECN are discussed at length, including those already included in [[RFC2481](#)] and backwards compatibility with implementations that would follow the specification in the obsoleted document.

[RFC 3540](#): "Robust Explicit Congestion Notification (ECN) Signaling with Nonces" (June 2003)

A nonce mechanism that makes use of the previously undefined bit combination that is defined in [[RFC2481](#)] is specified in this document, including the definition of a Nonce Sum (NS) field in the TCP header that would be necessary for ensuring that an ACK which does not indicate congestion is credible for the sender. The mechanism improves the robustness of congestion control by preventing receivers from exploiting ECN to gain an unfair share of network bandwidth.

[6.](#) Non-TCP Unicast Congestion Control

In the past, TCP dominated Internet traffic, as it was used for all of the predominant applications (SMTP, FTP, HTTP, TELNET). The majority of early congestion control work focused on TCP, and the introduction of congestion control into TCP alone is often credited with saving the Internet from additional congestion collapse events. Today, TCP has been joined by other transport protocols (e.g. SCTP, DCCP, RTP over UDP, etc.), and so having properly functioning congestion control within these other protocols is important for the Internet's health (as explained in [RFC 3714](#), for instance, or see the discussion of the "congestion control arms race" scenario in [RFC 2914](#)). Documents that describe unicast congestion control methods for non-TCP transport protocols have been grouped into this section. Note that SCTP is not discussed because its congestion control behavior is designed to be similar to TCP.

[RFC 3448](#): "TCP Friendly Rate Control (TFRC): Protocol Specification" (January 2003)

This document specifies TCP-Friendly Rate Control (TFRC), a rate-based congestion control mechanism for unicast flows operating in a best-effort Internet environment where flows are competing with standard TCP traffic. TFRC ensures conformance with TCP by continuously calculating the rate that a TCP sender would obtain

under similar circumstances using a slightly simplified version of the TCP Reno throughput equation in [[Pad98](#)]. Its sending rate is smoother than the rate of TCP, making it suitable for multimedia applications. TFRC is not a wire protocol but rather a mechanism which could, for instance, be used within a UDP based application, in a transport protocol such as RTP, or in the context of endpoint congestion management [[RFC3124](#)].

[RFC 3550](#): "RTP: A Transport Protocol for Real-Time Applications"
(July 2003)

This document specifies the real-time transport protocol RTP along with its control protocol RTCP. RTP/RTCP does not prescribe a specific congestion control behavior, but it is recommended that such a behavior be specified in each RTP profile (which is due to the fact that the potential for reducing the sending rate is often content dependent in the case of real-time streams). Specifically, [[RFC3550](#)] states: "For some profiles, it may be sufficient to include an applicability statement restricting the use of that profile to environments where congestion is avoided by engineering. For other profiles, specific methods such as data rate adaptation based on RTCP feedback may be required."

[[RFC4585](#)], which discusses RTCP feedback and adaptation mechanisms, points out that RTCP feedback may operate on much slower timescales than transport layer feedback mechanisms, and that additional mechanisms are therefore required to perform proper congestion control. One way to make use of such additional mechanisms is to run RTP over DCCP.

[RFC 4336](#): "Problem Statement for the Datagram Congestion Control Protocol (DCCP)" (March 2006)

This document provides the motivation leading to the design of DCCP. In doing so, other possibilities of implementing similar functionality are discussed, including unreliable extensions of SCTP, RTP based congestion control, and providing congestion control above or below UDP.

[RFC 4340](#): "Datagram Congestion Control Protocol" (March 2006)

This document specifies DCCP, the Datagram Congestion Control Protocol. This protocol provides bidirectional unicast connections of congestion-controlled unreliable datagrams. It is suitable for applications that transfer fairly large amounts of data and that can benefit from control over the tradeoff between timeliness and reliability. The core DCCP specification does not include a specific congestion control behavior; rather, it functions as a framework for such mechanisms, which can be selected via the Congestion Control Identifier (CCID).

[RFC 4341](#): "Profile for Datagram Congestion Control Protocol (DCCP) Congestion Control ID 2: TCP-like Congestion Control" (March 2006)

This is the specification of TCP-like congestion control for DCCP, which is chosen by selecting CCID 2. This should be used by senders who would like to take advantage of the available bandwidth in an environment with rapidly changing conditions, and who are able to adapt to the abrupt changes in the congestion window typical of TCP's Additive Increase Multiplicative Decrease (AIMD) congestion control.

[RFC 4342](#): "Profile for Datagram Congestion Control Protocol (DCCP) Congestion Control ID 3: TCP-Friendly Rate Control (TFRC)" (March 2006)

This is the specification of TCFRC congestion control as described

in [\[RFC3448\]](#) for DCCP, which is chosen by selecting CCID 3. This should be used by senders who want a TCP-friendly sending rate, possibly with Explicit Congestion Notification (ECN), while minimizing abrupt rate changes.

[7.](#) Multicast Congestion Control

In the IETF, congestion control for multicast (one-to-many) communication has primarily been tackled in the "Reliable Multicast

Transport" (RMT) Working Group. Except for [\[RFC2357\]](#) and [\[RFC3208\]](#), all the documents in this section were written by this group. Since a "one size fits all" protocol cannot meet the requirements of all possible applications, the approach taken is a modular one, consisting of "protocol cores" and "building blocks". YYY RMT RFCs not included because not very relevant for congestion control: 3269, 3451, 3452, 3453, 3695

[RFC 2357](#): "IETF Criteria for Evaluating Reliable Multicast Transport and Application Protocols" (June 1998)

Some early multicast content dissemination proposals did not incorporate proper congestion control; this is pointed out as being a severe mistake in [RFC 2357](#), as large-scale multicast applications have the potential to do vast congestion related damage. This document clearly makes the case that congestion control mechanisms should be developed and incorporated into multicast content dissemination protocols intended for use over the Internet.

[RFC 2887](#): "The Reliable Multicast Design Space for Bulk Data Transfer" (August 2000)

Several classes of potential congestion control schemes for single-sender multicast protocols are briefly sketched as possibilities, but no specific protocols are developed or selected in this document.

[RFC 3048](#): "Reliable Multicast Transport Building Blocks for One-to-Many Bulk-Data Transfer" (January 2001)

[RFC 3048](#) discusses the building block approach to RMT protocols and mentions that several different congestion control building blocks may be required in order to deal with different situations. Some of the possible interactions between building blocks for congestion control and those for FEC, acknowledgement, and group management are also mentioned.

[RFC 3208](#): "PGM Reliable Transport Protocol Specification" (December 2001)

As discussed in [RFC 3208](#)'s [Appendix B](#), a PGM protocol source can request congestion control feedback from both network elements (routers) and receivers (end hosts). These reports can indicate the load on the worst link in a particular path, or the load on the worst path. The actual procedure used in response to this feedback is not part of [RFC 3208](#), but the notion of using multicast routers to assist in congestion control is significant.

[RFC 3450](#): "Asynchronous Layered Coding (ALC) Protocol Instantiation" (December 2002)

This document specifies ALC, a rough header format using the RMT building blocks, that can be used by multicast content dissemination protocols. ALC is intended to use a multi-rate congestion control building block, where the sender does not require any feedback, but where multiple multicast groups with different transmission rates are available within an ALC session, and receivers control their rates by joining or leaving groups.

[RFC 3738](#): "Wave and Equation Based Rate Control (WEBRC) Building Block" (April 2004)

The abstract of [RFC 3738](#) is: "This document specifies Wave and Equation Based Rate Control (WEBRC), which provides rate and congestion control for data delivery. WEBRC is specifically designed to support protocols using IP multicast. It provides multiple-rate, congestion-controlled delivery to receivers, i.e., different receivers joined to the same session may be receiving packets at different rates depending on the bandwidths of their individual connections to the sender and on competing traffic along these connections. WEBRC requires no feedback from receivers to the sender, i.e., it is a completely receiver-driven congestion control protocol. Thus, it is designed to scale to potentially massive numbers of receivers attached to a session from a single sender. Furthermore, because each individual receiver adjusts to the available bandwidth between the sender and that receiver, there is the potential to deliver data to each individual receiver at the fastest possible rate for that receiver, even in a highly heterogeneous network architecture, using a single sender."

[RFC 3940](#): "NACK-Oriented Reliable Multicast Protocol (NORM)" (November 2004) and [RFC 3941](#) "NACK-Oriented Reliable Multicast (NORM) Building Blocks"

The NORM protocol incorporates a congestion control building block. A NORM sender can request congestion control information from receivers and use the TFMCC building block ([RFC 4654](#)) or PGMCC [[Riz00](#)] to provide congestion control, as discussed in the experimental NORM specification in [RFC 3940](#) and 3941.

[RFC 4654](#): "TCP-Friendly Multicast Congestion Control (TFMCC): Protocol Specification" (August 2006)

The abstract of [RFC 4654](#) is: " This document specifies TCP-Friendly Multicast Congestion Control (TFMCC). TFMCC is a congestion control mechanism for multicast transmissions in a best-effort Internet environment. It is a single-rate congestion control scheme, where the sending rate is adapted to the receiver experiencing the worst network conditions. TFMCC is reasonably fair when competing for bandwidth with TCP flows and has a relatively low variation of throughput over time, making it suitable for applications where a relatively smooth sending rate is of importance, such as streaming media."

[8.](#) Historic Interest

Early in the RFC series, there are many documents that merely contain an author's short thoughts on a subject or brief summaries from measurement and experimentation, rather than the result of a long formal IETF process. Some of the RFCs listed in this section have this distinction.

[RFC 889](#): "Internet Delay Experiments" (December 1983)

Based on reported measurement experiments, changes to the TCP retransmission timeout calculation are suggested in this document. It is noted that the original TCP RTO calculation leads to congestion when a delay spike occurs because it takes too long for the RTO to adapt, leading to superfluous retransmissions.

[RFC 896](#): "Congestion Control in IP/TCP Internetworks" (January 1984)

This is the first document known to the authors where the term "congestion collapse" was used. Here, it refers to the stable state which was observed when a sudden load on the net caused the round-trip time to rise faster than the sending hosts measured RTT could be updated. Two problems are discussed: the "small-packet problem" (now commonly known by the name "silly window syndrome") and the "source-quench problem", which is about inappropriately deciding when to send and how to react to ICMP source-quench messages. Solutions for these problems are presented.

[RFC 1254](#): "Gateway Congestion Control Survey" (August 1991)

This survey of congestion control approaches in routers first

discusses general congestion control performance goals (such as fairness), and then elaborates on the use of Source Quench messages, Random Drop (which would now be called "Active Queue Management"), Congestion Indication (DEC Bit) (an early form of ECN), "Selective Feedback Congestion Indication" (one particular method for applying ECN), and Fair Queuing. Finally, end system congestion control policies are discussed, including the well known algorithms in [[Jac88](#)] and their predecessor "CUTE".

[9.](#) Security Considerations

This document introduces no new security considerations. Each RFC listed in this document attempts to address the security considerations of the specification it contains.

[10.](#) IANA Considerations

This document contains no IANA considerations.

[11.](#) Acknowledgments

Several participants in the ICCRG contributed useful comments in the development of this document.

[12.](#) Informative References

- [Jac88] Jacobson, V., "Congestion Avoidance and Control, ACM SIGCOMM 1988 Proceedings, in ACM Computer Communication Review, 18 (4), pp. 314-329", 1988.
- [Pad98] Padhye, J., Firoiu, V., Towsley, D., and J. Kurose,

"Modeling TCP Throughput: A Simple Model and its Empirical Validation, Proc. ACM SIGCOMM 1998."

- [RFC0889] Mills, D., "Internet delay experiments", [RFC 889](#), December 1983.
- [RFC0896] Nagle, J., "Congestion control in IP/TCP internetworks", [RFC 896](#), January 1984.
- [RFC1254] Mankin, A. and K. Ramakrishnan, "Gateway Congestion Control Survey", [RFC 1254](#), August 1991.
- [RFC1958] Carpenter, B., "Architectural Principles of the Internet", [RFC 1958](#), June 1996.
- [RFC2309] Braden, B., Clark, D., Crowcroft, J., Davie, B., Deering, S., Estrin, D., Floyd, S., Jacobson, V., Minshall, G., Partridge, C., Peterson, L., Ramakrishnan, K., Shenker, S., Wroclawski, J., and L. Zhang, "Recommendations on Queue Management and Congestion Avoidance in the Internet", [RFC 2309](#), April 1998.
- [RFC2357] Mankin, A., Romanov, A., Bradner, S., and V. Paxson, "IETF Criteria for Evaluating Reliable Multicast Transport and Application Protocols", [RFC 2357](#), June 1998.
- [RFC2481] Ramakrishnan, K. and S. Floyd, "A Proposal to add Explicit Congestion Notification (ECN) to IP", [RFC 2481](#), January 1999.
- [RFC2884] Hadi Salim, J. and U. Ahmed, "Performance Evaluation of Explicit Congestion Notification (ECN) in IP Networks", [RFC 2884](#), July 2000.
- [RFC2887] Handley, M., Floyd, S., Whetten, B., Kermode, R., Vicisano, L., and M. Luby, "The Reliable Multicast Design

Space for Bulk Data Transfer", [RFC 2887](#), August 2000.

- [RFC2914] Floyd, S., "Congestion Control Principles", [BCP 41](#), [RFC 2914](#), September 2000.

- [RFC3048] Whetten, B., Vicisano, L., Kermode, R., Handley, M., Floyd, S., and M. Luby, "Reliable Multicast Transport Building Blocks for One-to-Many Bulk-Data Transfer", [RFC 3048](#), January 2001.
- [RFC3124] Balakrishnan, H. and S. Seshan, "The Congestion Manager", [RFC 3124](#), June 2001.
- [RFC3135] Border, J., Kojo, M., Griner, J., Montenegro, G., and Z. Shelby, "Performance Enhancing Proxies Intended to Mitigate Link-Related Degradations", [RFC 3135](#), June 2001.
- [RFC3150] Dawkins, S., Montenegro, G., Kojo, M., and V. Magret, "End-to-end Performance Implications of Slow Links", [BCP 48](#), [RFC 3150](#), July 2001.
- [RFC3168] Ramakrishnan, K., Floyd, S., and D. Black, "The Addition of Explicit Congestion Notification (ECN) to IP", [RFC 3168](#), September 2001.
- [RFC3208] Speakman, T., Crowcroft, J., Gemmell, J., Farinacci, D., Lin, S., Leshchiner, D., Luby, M., Montgomery, T., Rizzo, L., Tweedly, A., Bhaskar, N., Edmonstone, R., Sumanasekera, R., and L. Vicisano, "PGM Reliable Transport Protocol Specification", [RFC 3208](#), December 2001.
- [RFC3366] Fairhurst, G. and L. Wood, "Advice to link designers on link Automatic Repeat reQuest (ARQ)", [BCP 62](#), [RFC 3366](#), August 2002.
- [RFC3426] Floyd, S., "General Architectural and Policy Considerations", [RFC 3426](#), November 2002.
- [RFC3439] Bush, R. and D. Meyer, "Some Internet Architectural Guidelines and Philosophy", [RFC 3439](#), December 2002.
- [RFC3448] Handley, M., Floyd, S., Padhye, J., and J. Widmer, "TCP Friendly Rate Control (TFRC): Protocol Specification", [RFC 3448](#), January 2003.
- [RFC3449] Balakrishnan, H., Padmanabhan, V., Fairhurst, G., and M. Sooriyabandara, "TCP Performance Implications of Network Path Asymmetry", [BCP 69](#), [RFC 3449](#), December 2002.

- [RFC3450] Luby, M., Gemmell, J., Vicisano, L., Rizzo, L., and J. Crowcroft, "Asynchronous Layered Coding (ALC) Protocol Instantiation", [RFC 3450](#), December 2002.
- [RFC3540] Spring, N., Wetherall, D., and D. Ely, "Robust Explicit Congestion Notification (ECN) Signaling with Nonces", [RFC 3540](#), June 2003.
- [RFC3550] Schulzrinne, H., Casner, S., Frederick, R., and V. Jacobson, "RTP: A Transport Protocol for Real-Time Applications", STD 64, [RFC 3550](#), July 2003.
- [RFC3714] Floyd, S. and J. Kempf, "IAB Concerns Regarding Congestion Control for Voice Traffic in the Internet", [RFC 3714](#), March 2004.
- [RFC3738] Luby, M. and V. Goyal, "Wave and Equation Based Rate Control (WEBRC) Building Block", [RFC 3738](#), April 2004.
- [RFC3819] Karn, P., Bormann, C., Fairhurst, G., Grossman, D., Ludwig, R., Mahdavi, J., Montenegro, G., Touch, J., and L. Wood, "Advice for Internet Subnetwork Designers", [BCP 89](#), [RFC 3819](#), July 2004.
- [RFC3926] Paila, T., Luby, M., Lehtonen, R., Roca, V., and R. Walsh, "FLUTE - File Delivery over Unidirectional Transport", [RFC 3926](#), October 2004.
- [RFC3940] Adamson, B., Bormann, C., Handley, M., and J. Macker, "Negative-acknowledgment (NACK)-Oriented Reliable Multicast (NORM) Protocol", [RFC 3940](#), November 2004.
- [RFC3941] Adamson, B., Bormann, C., Handley, M., and J. Macker, "Negative-Acknowledgment (NACK)-Oriented Reliable Multicast (NORM) Building Blocks", [RFC 3941](#), November 2004.
- [RFC4336] Floyd, S., Handley, M., and E. Kohler, "Problem Statement for the Datagram Congestion Control Protocol (DCCP)", [RFC 4336](#), March 2006.
- [RFC4340] Kohler, E., Handley, M., and S. Floyd, "Datagram Congestion Control Protocol (DCCP)", [RFC 4340](#), March 2006.
- [RFC4341] Floyd, S. and E. Kohler, "Profile for Datagram Congestion Control Protocol (DCCP) Congestion Control ID 2: TCP-like Congestion Control", [RFC 4341](#), March 2006.

Internet-Draft

Congestion Control RFCs

July 2006

- [RFC4342] Floyd, S., Kohler, E., and J. Padhye, "Profile for Datagram Congestion Control Protocol (DCCP) Congestion Control ID 3: TCP-Friendly Rate Control (TFRC)", [RFC 4342](#), March 2006.
- [RFC4585] Ott, J., Wenger, S., Sato, N., Burmeister, C., and J. Rey, "Extended RTP Profile for Real-time Transport Control Protocol (RTCP)-Based Feedback (RTP/AVPF)", [RFC 4585](#), July 2006.
- [RFC4614] Duke, M., Braden, R., Eddy, W., and E. Blanton, "A Roadmap for Transmission Control Protocol (TCP) Specification Documents", [RFC 4614](#), September 2006.
- [RFC4654] Widmer, J. and M. Handley, "TCP-Friendly Multicast Congestion Control (TFMCC): Protocol Specification", [RFC 4654](#), August 2006.
- [Riz00] Rizzo, L., "pgmcc: A TCP-Friendly Single-Rate Multicast Congestion Control Scheme", Proceedings of ACM SIGCOMM 2000, August 2000.

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