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RTP Congestion Control: Circuit Breakers for Unicast Sessions
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Abstract

The Real-time Transport Protocol (RTP) is widely used in telephony, video conferencing, and telepresence applications. Such applications are often run on best-effort UDP/IP networks. If congestion control is not implemented in the applications, then network congestion will deteriorate the user's multimedia experience. This document does not propose a congestion control algorithm; rather, it defines a minimal set of "circuit-breakers". Circuit-breakers are conditions under which an RTP flow is expected to stop transmitting media to protect the network from excessive congestion. It is expected that all RTP applications running on best-effort networks will be able to run without triggering these circuit breakers in normal operation. Any future RTP congestion control specification is expected to operate within the envelope defined by these circuit breakers.

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1. Introduction

The Real-time Transport Protocol (RTP) [RFC3550] is widely used in voice-over-IP, video teleconferencing, and telepresence systems. Many of these systems run over best-effort UDP/IP networks, and can suffer from packet loss and increased latency if network congestion occurs. Designing effective RTP congestion control algorithms, to adapt the transmission of RTP-based media to match the available network capacity, while also maintaining the user experience, is a difficult but important problem. Many such congestion control and media adaptation algorithms have been proposed, but to date there is no consensus on the correct approach, or even that a single standard algorithm is desirable.

This memo does not attempt to propose a new RTP congestion control algorithm. Rather, it proposes a minimal set of "circuit breakers"; conditions under which there is general agreement that an RTP flow is causing serious congestion, and ought to cease transmission. It is expected that future standards-track congestion control algorithms for RTP will operate within the envelope defined by this memo.

2. 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]. This interpretation of these key words applies only when written in ALL CAPS. Mixed- or lower-case uses of these key words are not to be interpreted as carrying special significance in this memo.

3. Background

We consider congestion control for unicast RTP traffic flows. This is the problem of adapting the transmission of an audio/visual data flow, encapsulated within an RTP transport session, from one sender to one receiver, so that it matches the available network bandwidth. Such adaptation needs to be done in a way that limits the disruption to the user experience caused by both packet loss and excessive rate changes. Congestion control for multicast flows is outside the scope of this memo.

Congestion control for unicast RTP traffic can be implemented in one of two places in the protocol stack. One approach is to run the RTP traffic over a congestion controlled transport protocol, for example over TCP, and to adapt the media encoding to match the dictates of the transport-layer congestion control algorithm. This is safe for

the network, but can be suboptimal for the media quality unless the transport protocol is designed to support real-time media flows. We do not consider this class of applications further in this memo, as their network safety is guaranteed by the underlying transport.

Alternatively, RTP flows can be run over a non-congestion controlled transport protocol, for example UDP, performing rate adaptation at the application layer based on RTP Control Protocol (RTCP) feedback. With a well-designed, network-aware, application, this allows highly effective media quality adaptation, but there is potential to disrupt the network's operation if the application does not adapt its sending rate in a timely and effective manner. We consider this class of applications in this memo.

Congestion control relies on monitoring the delivery of a media flow, and responding to adapt the transmission of that flow when there are signs that the network path is congested. Network congestion can be detected in one of three ways: 1) a receiver can infer the onset of congestion by observing an increase in one-way delay caused by queue build-up within the network; 2) if Explicit Congestion Notification (ECN) [RFC3168] is supported, the network can signal the presence of congestion by marking packets using ECN Congestion Experienced (CE) marks; or 3) in the extreme case, congestion will cause packet loss that can be detected by observing a gap in the received RTP sequence numbers. Once the onset of congestion is observed, the receiver has to send feedback to the sender to indicate that the transmission rate needs to be reduced. How the sender reduces the transmission rate is highly dependent on the media codec being used, and is outside the scope of this memo.

There are several ways in which a receiver can send feedback to a media sender within the RTP framework:

- The base RTP specification [RFC3550] defines RTCP Reception Report (RR) packets to convey reception quality feedback information, and Sender Report (SR) packets to convey information about the media transmission. RTCP SR packets contain data that can be used to reconstruct media timing at a receiver, along with a count of the total number of octets and packets sent. RTCP RR packets report on the fraction of packets lost in the last reporting interval, the cumulative number of packets lost, the highest sequence number received, and the inter-arrival jitter. The RTCP RR packets also contain timing information that allows the sender to estimate the network round trip time (RTT) to the receivers. RTCP reports are sent periodically, with the reporting interval being determined by the number of participants in the session and a configured session bandwidth estimate. The interval between reports sent from each receiver tends to be on the order of a few seconds on average, and

it is randomised to avoid synchronisation of reports from multiple receivers. RTCP RR packets allow a receiver to report ongoing network congestion to the sender. However, if a receiver detects the onset of congestion partway through a reporting interval, the base RTP specification contains no provision for sending the RTCP RR packet early, and the receiver has to wait until the next scheduled reporting interval.

- The RTCP Extended Reports (XR) [RFC3611] allow reporting of more complex and sophisticated reception quality metrics, but do not change the RTCP timing rules. RTCP extended reports of potential interest for congestion control purposes are the extended packet loss, discard, and burst metrics [RFC3611], [I-D.ietf-xrblock-rtcp-xr-discard], [I-D.ietf-xrblock-rtcp-xr-discard-rle-metrics], [I-D.ietf-xrblock-rtcp-xr-burst-gap-discard], [I-D.ietf-xrblock-rtcp-xr-burst-gap-loss]; and the extended delay metrics [I-D.ietf-xrblock-rtcp-xr-delay], [I-D.ietf-xrblock-rtcp-xr-pdv]. Other RTCP Extended Reports that could be helpful for congestion control purposes might be developed in future.

- Rapid feedback about the occurrence of congestion events can be achieved using the Extended RTP Profile for RTCP-Based Feedback (RTP/AVPF) [RFC4585] in place of the more common RTP/AVP profile [RFC3551]. This modifies the RTCP timing rules to allow RTCP reports to be sent early, in some cases immediately, provided the average RTCP reporting interval remains unchanged. It also defines new transport-layer feedback messages, including negative acknowledgements (NACKs), that can be used to report on specific congestion events. The use of the RTP/AVPF profile is dependent on signalling, but is otherwise generally backwards compatible, as it keeps the same average RTCP reporting interval as the base RTP specification. The RTP Codec Control Messages [RFC5104] extend the RTP/AVPF profile with additional feedback messages that can be used to influence that way in which rate adaptation occurs. The dynamics of how rapidly feedback can be sent are unchanged.

- Finally, Explicit Congestion Notification (ECN) for RTP over UDP [RFC6679] can be used to provide feedback on the number of packets that received an ECN Congestion Experienced (CE) mark. This RTCP extension builds on the RTP/AVPF profile to allow rapid congestion feedback when ECN is supported.

In addition to these mechanisms for providing feedback, the sender can include an RTP header extension in each packet to record packet transmission times. There are two methods: [RFC5450] represents the transmission time in terms of a time-offset from the RTP timestamp of

the packet, while [RFC6051] includes an explicit NTP-format sending timestamp (potentially more accurate, but a higher header overhead). Accurate sending timestamps can be helpful for estimating queuing delays, to get an early indication of the onset of congestion.

Taken together, these various mechanisms allow receivers to provide feedback on the senders when congestion events occur, with varying degrees of timeliness and accuracy. The key distinction is between systems that use only the basic RTCP mechanisms, without RTP/AVPF rapid feedback, and those that use the RTP/AVPF extensions to respond to congestion more rapidly.

4. RTP Circuit Breakers for Systems Using the RTP/AVP Profile

The feedback mechanisms defined in [RFC3550] and available under the RTP/AVP profile [RFC3551] are the minimum that can be assumed for a baseline circuit breaker mechanism that is suitable for all unicast applications of RTP. Accordingly, for an RTP circuit breaker to be useful, it needs to be able to detect that an RTP flow is causing excessive congestion using only basic RTCP features, without needing RTCP XR feedback or the RTP/AVPF profile for rapid RTCP reports.

Three potential congestion signals are available from the basic RTCP SR/RR packets and are reported for each synchronisation source (SSRC) in the RTP session:

1. The sender can estimate the network round-trip time once per RTCP reporting interval, based on the contents and timing of RTCP SR and RR packets.

2. Receivers report a jitter estimate (the statistical variance of the RTP data packet inter-arrival time) calculated over the RTCP reporting interval. Due to the nature of the jitter calculation ([RFC3550], section 6.4.4), the jitter is only meaningful for RTP flows that send a single data packet for each RTP timestamp value (i.e., audio flows, or video flows where each frame comprises one RTP packet).

3. Receivers report the fraction of RTP data packets lost during the RTCP reporting interval, and the cumulative number of RTP packets lost over the entire RTP session.

These congestion signals limit the possible circuit breakers, since they give only limited visibility into the behaviour of the network.

RTT estimates are widely used in congestion control algorithms, as a proxy for queuing delay measures in delay-based congestion control or

to determine connection timeouts. RTT estimates derived from RTCP SR and RR packets sent according to the RTP/AVP timing rules are far too infrequent to be useful though, and don't give enough information to distinguish a delay change due to routing updates from queuing delay caused by congestion. Accordingly, we cannot use the RTT estimate alone as an RTP circuit breaker.

Increased jitter can be a signal of transient network congestion, but in the highly aggregated form reported in RTCP RR packets, it offers insufficient information to estimate the extent or persistence of congestion. Jitter reports are a useful early warning of potential network congestion, but provide an insufficiently strong signal to be used as a circuit breaker.

The remaining congestion signals are the packet loss fraction and the cumulative number of packets lost. These are robust indicators of congestion in a network where packet loss is primarily due to queue overflows, although less accurate in networks where losses can be caused by non-congestive packet corruption. TCP uses packet loss as a congestion signal.

Two packet loss regimes can be observed: 1) RTCP RR packets show a non-zero packet loss fraction, while the extended highest sequence number received continues to increment; and 2) RR packets show a loss fraction of zero, but the extended highest sequence number received does not increment even though the sender has been transmitting RTP data packets. The former corresponds to the TCP congestion avoidance state, and indicates a congested path that is still delivering data; the latter corresponds to a TCP timeout, and is most likely due to a path failure. We derive circuit breaker conditions for these two loss regimes in the following.

4.1. RTP/AVP Circuit Breaker #1: Media Timeout

If RTP data packets are being sent while the corresponding RTCP RR packets report a non-increasing extended highest sequence number received, this is an indication that those RTP data packets are not reaching the receiver. This could be a short-term issue affecting only a few packets, perhaps caused by a slow-to-open firewall or a transient connectivity problem, but if the issue persists, it is a sign of a more ongoing and significant problem. Accordingly, if a sender of RTP data packets receives two or more consecutive RTCP RR packets from the same receiver that correspond to its transmission, and have a non-increasing extended highest sequence number received field (i.e., at least three RTCP RR packets that report the same value in the extended highest sequence number received field, when the sender has sent data packets that would have caused an increase in the reported value of the extended highest sequence number

received if they had reached the receiver), then that sender SHOULD cease transmission. What it means to cease transmission depends on the application, but the intention is that the application will stop sending RTP data packets until the user makes an explicit attempt to restart the call (RTP flows halted by the circuit breaker SHOULD NOT be restarted automatically unless the sender has received information that the congestion has dissipated).

Systems that usually send at a high data rate, but that can reduce their data rate significantly (i.e., by at least a factor of ten), MAY first reduce their sending rate to this lower value to see if this resolves the congestion, but MUST then cease transmission if the problem does not resolve itself within a further two RTCP reporting intervals. An example of this might be a video conferencing system that backs off to sending audio only, before completely dropping the call. If such a reduction in sending rate resolves the congestion problem, the sender MAY gradually increase the rate at which it sends data after a reasonable amount of time has passed, provided it takes care not to cause the problem to recur ("reasonable" is intentionally not defined here).

The choice of two RTCP reporting intervals is to give enough time for transient problems to resolve themselves, but to stop problem flows quickly enough to avoid causing serious ongoing network congestion. A single RTCP report showing no reception could be caused by numerous transient faults, and so will not cease transmission. Waiting for more than two RTCP reports before stopping a flow might avoid some false positives, but would lead to problematic flows running for a long time before being cut off.

4.2. RTP/AVP Circuit Breaker #2: RTCP Timeout

In addition to media timeouts, as were discussed in Section 4.1, an RTP session has the possibility of an RTCP timeout. This can occur when RTP data packets are being sent, but there are no RTCP reports returned from the receiver. This is either due to a failure of the receiver to send RTCP reports, or a failure of the return path that is preventing those RTCP reporting from being delivered.

According to RFC 3550 [RFC3550], any participant that has not sent an RTCP packet within the last two RTCP intervals is removed from the sender list. Therefore, an RTP sender SHOULD cease transmission if it does not receive a single RTCP RR packet and during this period has sent 3 RTCP SR packets to the RTP receiver. Similarly, the same circuit breaker rule applies to an RTCP receiver which has not received a single SR packet, and in the corresponding period it has sent 3 RTCP RR packets. What it means to cease transmission depends on the application, but the intention is that the application will

stop sending RTP data packets until the user makes an explicit attempt to restart the call (RTP flows halted by the circuit breaker SHOULD NOT be restarted automatically unless the sender has received information that the congestion has dissipated).

4.3. RTP/AVP Circuit Breaker #3: Congestion

If RTP data packets are being sent, and the corresponding RTCP RR packets show non-zero packet loss fraction and increasing extended highest sequence number received, then those RTP data packets are arriving at the receiver, but some degree of congestion is occurring. The RTP/AVP profile [RFC3551] states that:

> If best-effort service is being used, RTP receivers SHOULD monitor packet loss to ensure that the packet loss rate is within acceptable parameters. Packet loss is considered acceptable if a TCP flow across the same network path and experiencing the same network conditions would achieve an average throughput, measured on a reasonable time scale, that is not less than the RTP flow is achieving. This condition can be satisfied by implementing congestion control mechanisms to adapt the transmission rate (or the number of layers subscribed for a layered multicast session), or by arranging for a receiver to leave the session if the loss rate is unacceptably high.
>
> The comparison to TCP cannot be specified exactly, but is intended as an "order-of-magnitude" comparison in time scale and throughput. The time scale on which TCP throughput is measured is the round-trip time of the connection. In essence, this requirement states that it is not acceptable to deploy an application (using RTP or any other transport protocol) on the best-effort Internet which consumes bandwidth arbitrarily and does not compete fairly with TCP within an order of magnitude.

The phase "order of magnitude" in the above means within a factor of ten, approximately. In order to implement this, it is necessary to estimate the throughput a TCP connection would achieve over the path. For a long-lived TCP Reno connection, Padhye et al. [Padhye] showed that the throughput can be estimated using the following equation:

$$X = \frac{s}{R*\sqrt{2*b*p/3} + (t_RTO * (3*\sqrt{3*b*p/8} * p * (1+32*p^2)))}$$

where:

X is the transmit rate in bytes/second.

s is the packet size in bytes. If data packets vary in size, then the average size is to be used.

R is the round trip time in seconds.

p is the loss event rate, between 0 and 1.0, of the number of loss events as a fraction of the number of packets transmitted.

t_RTO is the TCP retransmission timeout value in seconds, approximated by setting t_RTO = 4*R.

b is the number of packets acknowledged by a single TCP acknowledgement ([RFC3448] recommends the use of b=1 since many TCP implementations do not use delayed acknowledgements).

This is the same approach to estimated TCP throughput that is used in [RFC3448]. Under conditions of low packet loss, this formula can be approximated as follows with reasonable accuracy:

$$X = \frac{s}{R * \sqrt{p*2/3}}$$

It is RECOMMENDED that this simplified throughout equation be used, since the reduction in accuracy is small, and it is much simpler to calculate than the full equation.

Given this TCP equation, two parameters need to be estimated and reported to the sender in order to calculate the throughput: the round trip time, R, and the loss event rate, p (the packet size, s, is known to the sender). The round trip time can be estimated from RTCP SR and RR packets. This is done too infrequently for accurate statistics, but is the best that can be done with the standard RTCP mechanisms.

RTCP RR packets contain the packet loss fraction, rather than the loss event rate, so p cannot be reported (TCP typically treats the loss of multiple packets within a single RTT as one loss event, but RTCP RR packets report the overall fraction of packets lost, not caring about when the losses occurred). Using the loss fraction in place of the loss event rate can overestimate the loss. We believe that this overestimate will not be significant, given that we are only interested in order of magnitude comparison ([Floyd] section 3.2.1 shows that the difference is small for steady-state conditions and random loss, but using the loss fraction is more conservative in the case of bursty loss).

The congestion circuit breaker is therefore: when RTCP RR packets are received, estimate the TCP throughput using the simplified equation above, and the measured R, p (approximated by the loss fraction), and s. Compare this with the actual sending rate. If the actual sending rate is more than ten times the estimated sending rate derived from the TCP throughput equation for two consecutive RTCP reporting intervals, the sender SHOULD cease transmission. What it means to cease transmission depends on the application, but the intention is that the application will stop sending RTP data packets until the user makes an explicit attempt to restart the call (RTP flows halted by the circuit breaker SHOULD NOT be restarted automatically unless the sender has received information that the congestion has dissipated).

Systems that usually send at a high data rate, but that can reduce their data rate significantly (i.e., by at least a factor of ten), MAY first reduce their sending rate to this lower value to see if this resolves the congestion, but MUST then cease transmission if the problem does not resolve itself within a further two RTCP reporting intervals. An example of this might be a video conferencing system that backs off to sending audio only, before completely dropping the call. If such a reduction in sending rate resolves the congestion problem, the sender MAY gradually increase the rate at which it sends data after a reasonable amount of time has passed, provided it takes care not to cause the problem to recur ("reasonable" is intentionally not defined here).

As in Section 4.1, we use two reporting intervals to avoid triggering the circuit breaker on transient failures. This circuit breaker is a worst-case condition, and congestion control needs to be performed to keep well within this bound. It is expected that the circuit breaker will only be triggered if the usual congestion control fails for some reason.

5. RTP Circuit Breakers for Systems Using the RTP/AVPF Profile

Use of the Extended RTP Profile for RTCP-based Feedback (RTP/AVPF) [RFC4585] allows receivers to send early RTCP reports in some cases, to inform the sender about particular events in the media stream. There are several use cases for such early RTCP reports, including providing rapid feedback to a sender about the onset of congestion.

Receiving rapid feedback about congestion events potentially allows congestion control algorithms to be more responsive, and to better adapt the media transmission to the limitations of the network. It is expected that many RTP congestion control algorithms will adopt the RTP/AVPF profile for this reason, defining new transport layer

feedback reports that suit their requirements. Since these reports are not yet defined, and likely very specific to the details of the congestion control algorithm chosen, they cannot be used as part of the generic RTP circuit breaker.

If the extension for Reduced-Size RTCP [RFC5506] is not used, early RTCP feedback packets sent according to the RTP/AVPF profile will be compound RTCP packets that include an RTCP SR/RR packet. That RTCP SR/RR packet MUST be processed as if it were sent as a regular RTCP report and counted towards the circuit breaker conditions specified in Section 4.1 and Section 4.3 of this memo. This will potentially make the RTP circuit breaker fire earlier than it would if the RTP/AVPF profile was not used.

Reduced-size RTCP reports sent under to the RTP/AVPF early feedback rules that do not contain an RTCP SR or RR packet MUST be ignored by the RTP circuit breaker (they do not contain the information used by the circuit breaker algorithm). In this case, the circuit breaker will only use the information contained in the periodic RTCP SR/RR packets. This allows the use of low-overhead early RTP/AVPF feedback without triggering the RTP circuit breaker, and so is suitable for RTP congestion control algorithms that need to quickly report loss events in between regular RTCP reports.

6. Impact of RTCP XR

RTCP Extended Report (XR) blocks provide additional reception quality metrics, but do not change the RTCP timing rules. Some of the RTCP XR blocks provide information that might be useful for congestion control purposes, others provided non-congestion-related metrics. The presence of RTCP XR blocks in a compound RTCP packet does not affect the RTP circuit breaker algorithm; for consistency and ease of implementation, only the reception report blocks contained in RTCP SR or RR packets are used by the RTP circuit breaker algorithm.

7. Impact of Explicit Congestion Notification (ECN)

ECN-CE marked packets SHOULD be treated as if it were lost for the purposes of congestion control, when determining the optimal media sending rate for an RTP flow. If an RTP sender has negotiated ECN support for an RTP session, and has successfully initiated ECN use on the path to the receiver [RFC6679], then ECN-CE marked packets SHOULD be treated as if they were lost when calculating if the congestion-based RTP circuit breaker (Section 4.3) has been met.

The use of ECN for RTP flows does not affect the media timeout RTP

circuit breaker (Section 4.1) or the RTCP timeout circuit breaker (Section 4.2), since these are both connectivity checks that simply determinate if any packets are being received.

8. Security Considerations

The security considerations of [RFC3550] apply.

If the RTP/AVPF profile is used to provide rapid RTCP feedback, the security considerations of [RFC4585] apply. If ECN feedback for RTP over UDP/IP is used, the security considerations of [RFC6679] apply.

If non-authenticated RTCP reports are used, an on-path attacker can trivially generate fake RTCP packets that indicate high packet loss rates, causing the circuit breaker to trigger and disrupting an RTP session. This is somewhat more difficult for an off-path attacker, due to the need to guess the randomly chosen RTP SSRC value and the RTP sequence number. This attack can be avoided if RTCP packets are authenticated, for example using the Secure RTP profile [RFC3711].

9. IANA Considerations

There are no actions for IANA.

10. Acknowledgements

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