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CoAP Simple Congestion Control/Advanced
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Abstract

CoAP, the Constrained Application Protocol, needs to be implemented in such a way that it does not cause persistent congestion on the network it uses. The CoRE CoAP specification defines basic behavior that exhibits low risk of congestion with minimal implementation requirements. It also leaves room for combining the base specification with advanced congestion control mechanisms with higher performance.

This specification defines more advanced, but still simple CoRE Congestion Control mechanisms, called CoCoA. The core of these mechanisms is a Retransmission TimeOut (RTO) algorithm that makes use of Round-Trip Time (RTT) estimates, in contrast with how the RTO is determined as per the base CoAP specification ([RFC 7252](#)). The mechanisms defined in this document have relatively low complexity, yet they improve the default CoAP RTO algorithm. The design of the mechanisms in this specification has made use of input from simulations and experiments in real networks.

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1. Introduction

CoAP, the Constrained Application Protocol, needs to be implemented in such a way that it does not cause persistent congestion on the network it uses. The CoRE CoAP specification defines basic behavior that exhibits low risk of congestion with minimal implementation requirements. It also leaves room for combining the base specification with advanced congestion control mechanisms with higher performance.

The present specification defines such an advanced CoRE Congestion Control mechanism, with the goal of improving performance while retaining safety as well as the simplicity that is appropriate for constrained devices. Hence, we are calling this mechanism Simple Congestion Control/Advanced, or CoCoA for short.

CoCoA calculates the retransmission time-out (RTO) based on RTT estimations with and without loss. By taking retransmissions (in a potentially lossy network) into account when estimating the RTT, this algorithm reacts to congestion with a lower sending rate. For non-confirmable packets, it also limits the sending rate to $1/\text{RTO}$; assuming that the RTO estimation in CoCoA works as expected, RTO should be slightly greater than the RTT, thus CoCoA would be more conservative than the original specification in [RFC7641].

In the Internet, congestion control is typically implemented in a way that it can be introduced or upgraded unilaterally. Still, a new congestion control scheme must not be introduced lightly. To ensure that the new scheme is not posing a danger to the network, considerable work has been done on simulations and experiments in real networks. Some of this work will be mentioned in "Discussion" subsections in the following sections; an overview is given in [Appendix A](#). Extended rationale for this specification can also be found in the historical Internet-Drafts [[I-D.bormann-core-congestion-control](#)] and [[I-D.eggert-core-congestion-control](#)], as well as in the minutes of the IETF 84 CoRE WG meetings.

1.1. Terminology

This specification uses terms from [RFC7252]. In addition, it defines the following terminology:

Initiator: The endpoint that sends the message that initiates an exchange. E.g., the party that sends a confirmable message, or a non-confirmable message (see [Section 4.3 of \[RFC7252\]](#)) conveying a request.

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.

The term "byte", abbreviated by "B", is used in its now customary sense as a synonym for "octet".

2. Context

In the definition of the CoAP protocol [\[RFC7252\]](#), an approach was taken that includes a very simple basic scheme (lock-step with the number of parallel exchanges usually limited to 1) in the base specification together with performance-enhancing advanced mechanisms.

The present specification is based on the approved text in the [\[RFC7252\]](#) base specification. It is making use of the text that permits advanced congestion control mechanisms and allows them to change protocol parameters, including NSTART and the binary exponential backoff mechanism. Note that [Section 4.8 of \[RFC7252\]](#) limits the leeway that implementations have in changing the CoRE protocol parameters.

The present specification also assumes that, outside of exchanges, non-confirmable messages can only be used at a limited rate without an advanced congestion control mechanism (this is mainly relevant for [\[RFC7641\]](#)). It is also intended to address the [\[RFC8085\]](#) guideline about combining congestion control state for a destination; and to clarify its meaning for CoAP using the definition of an endpoint.

The present specification does not address multicast or dithering beyond basic retransmission dithering.

3. Area of Applicability

The present algorithm is intended to be generally applicable. The objective is to be "better" than default CoAP congestion control in a number of characteristics, including achievable goodput for a given offered load, latency, and recovery from bursts, while providing more predictable stress to the network and the same level of safety from catastrophic congestion. The algorithm defined in this document is

intended to adapt to the current characteristics of any underlying network, and therefore is well suited for a wide range of network conditions, in terms of bandwidth, latency, load, loss rate, topology, etc. In particular, CoCoA has been found to perform well in scenarios with latencies ranging from the order of milliseconds to peaks of dozens of seconds, as well as in single-hop and multihop topologies. Link technologies used in existing evaluation work comprise IEEE 802.15.4, GPRS, UMTS and Wi-Fi (see [Appendix A](#)). CoCoA is also expected to work suitably across the general Internet. The algorithm does require three state variables per scope plus the state needed to do RTT measurements, so it may not be applicable to the most constrained devices (say, class 1 as per [\[RFC7228\]](#)).

The scope of each instance of the algorithm in the current set of evaluations has been the five-tuple, i.e., CoAP + endpoint (transport address) for Initiator and Responder. Potential applicability to larger scopes needs to be examined.

4. Advanced CoAP Congestion Control: RTO Estimation

For an initiator that plans to make multiple requests to one destination endpoint, it may be worthwhile to make RTT measurements in order to compute a more appropriate RTO than the default initial timeout of 2 to 3 s. In particular, a wide spectrum of RTT values is expected in different types of networks where CoAP is used. Those RTTs range from several orders of magnitude below the default initial timeout to values larger than the default. The algorithm defined in this document is based on the algorithm for RTO estimation defined in [\[RFC6298\]](#), with appropriately extended default/base values, as proposed in [Section 4.2.1](#). Note that such a mechanism must, during idle periods, decay RTO estimates that are shorter or longer than the default RTO estimate back to the default RTO estimate, until fresh measurements become available again, as proposed in [Section 4.3](#).

RTT variability challenges RTO estimation. In TCP, delayed ACKs contribute to RTT variability, since this option adds a delay of up to 500 ms (typically, 200 ms) before an ACK is sent by a receiving TCP endpoint. However, one important consideration not relevant for TCP is the fact that a CoAP round-trip may include application processing time, which may be hard to predict, and may differ between different resources available at the same endpoint. Also, for communications with networks of constrained devices that apply radio duty cycling, large and variable round-trip times are likely to be observed. Servers will only trigger their early ACKs (with a non-piggybacked response to be sent later) based on the default timers, e.g. after 1 s. A client that has arrived at a RTO estimate shorter than 1 s SHOULD therefore use a larger backoff factor for retransmissions to avoid expending all of its retransmissions

(MAX_RETRANSMIT, see [Section 4.2 of \[RFC7252\]](#), normally 4) in the default interval of 2 to 3 s. The approach chosen for a mechanism with variable backoff factors is presented in [Section 4.2.1](#).

It may also be worthwhile to perform RTT estimation not just based on information measured from a single destination endpoint, but also based on entire hosts (IP addresses) and/or complete prefixes (e.g., maintain an RTT estimate for a whole /64). The exact way this can be used to reduce the amount of state in an initiator is for further study.

4.1. Blind RTO Estimate

The initial RTO estimate for an endpoint is set to 2 seconds (the initial RTO estimate is used as the initial value for both `E_weak_` and `E_strong_` below).

If only the initial RTO estimate is available, the RTO estimate for each of up to NSTART exchanges started in parallel is set to 2 s times the number of parallel exchanges, e.g. if two exchanges are already running, the initial RTO estimate for an additional exchange is 6 seconds.

4.2. Measurement-based RTO Estimate

The RTO estimator runs two copies of the algorithm defined in [\[RFC6298\]](#), using the same variables and calculations to estimate the RTO, with the differences introduced in [Section 4.2.1](#): One copy for exchanges that complete on initial transmissions (the "strong estimator", `E_strong_`), and one copy for exchanges that have run into retransmissions, where only the first two retransmissions are considered (the "weak estimator", `E_weak_`). For the latter, there is some ambiguity whether a response is based on the initial transmission or the retransmissions. For the purposes of the weak estimator, the time from the initial transmission counts. Responses obtained after the third retransmission are not used to update an estimator.

The overall RTO estimate is an exponentially weighted moving average computed of the strong and the weak estimator, which is evolved after each contribution to the weak estimator (1) or to the strong estimator (2), from the estimator (either the weak or strong estimator) that made the most recent contribution:

$$\text{RTO} := w_{\text{weak}} * E_{\text{weak_}} + (1 - w_{\text{weak}}) * \text{RTO} \quad (1)$$

$$\text{RTO} := w_{\text{strong}} * E_{\text{strong_}} + (1 - w_{\text{strong}}) * \text{RTO} \quad (2)$$

(Splitting this update into the two cases avoids making the contribution of the weak estimator too big in naturally lossy networks.)

The default values for the corresponding weights, `w_weak` and `w_strong`, are 0.25 and 0.5, respectively. These values have been found to offer good performance in evaluations (see [Appendix A](#)). Pseudocode and examples for the overall RTO estimate presented are available in [Appendix B.1](#) and [Appendix C.1](#).

4.2.1. Differences with the algorithm of [RFC 6298](#)

This subsection presents three differences of the algorithm defined in this document with the one defined in [\[RFC6298\]](#). The first two recommend new parameter settings. The third one is the variable backoff factor (VBF), which replaces [RFC6298](#)'s simple exponential backoff that always multiplies the RTO by a factor of 2 when the RTO timer expires.

The initial value for each of the two RTO estimators is 2 s.

For the weak estimator, the factor `K` (the RTT variance multiplier) is set to 1 instead of 4. This is necessary to avoid a strong increase of the RTO in the case that the `RTTVAR` value is very large, which may be the case if a weak RTT measurement is obtained after one or more retransmissions.

In order to avoid that exchanges with small initial RTOs (i.e. RTO estimate lower than 1 s) use up all retransmissions in a short interval of time, the RTO for a retransmission is multiplied by 3 for each retransmission as long as the RTO is less than 1 s.

On the other hand, to avoid exchanges with large initial RTOs (i.e., RTO estimate greater than 3 s) not being able to carry out all retransmissions within `MAX_TRANSMIT_WAIT` (normally 93 s), the RTO is multiplied only by 1.5 when RTO is greater than 3 s.

Pseudocode for the variable backoff factor is in [Appendix B.3](#).

The binary exponential backoff is truncated at 32 seconds. Similar to the way retransmissions are handled in the base specification, they are dithered between `1 x RTO` and `ACK_RANDOM_FACTOR x RTO`.

4.2.2. Discussion

In contrast to [\[RFC6298\]](#), this algorithm attempts to make use of ambiguous information from retransmissions. This is motivated by the high non-congestion loss rates expected in constrained node networks,

and the need to update the RTO estimators even in the presence of loss. This approach appears to contravene the mandate in [Section 3.1.1 of \[RFC8085\]](#) that "latency samples MUST NOT be derived from ambiguous transactions". However, those samples are not simply combined into the strong estimator, but are used to correct the limited knowledge that can be gained from the strong RTT measurements by employing an additional weak estimator. In fact, the weak estimator allows to better update the RTO estimator when mostly weak RTTs are available, either due to the lossy nature of links or due to congestion-induced losses. In the presence of the latter, and compared to a strong-only estimator ($w_{\text{weak}}=0$), spurious timeouts are avoided and the rate of retries is reduced, which allows to decrease congestion. Evidence that has been collected from experiments appears to support that the overall effect of using this data in the way described is beneficial (Appendix A).

Some evaluation has been done on earlier versions of this specification [[Betzler2013](#)]. A more recent (and more comprehensive) reference is [[Betzler2015](#)].

4.3. Lifetime, Aging

The state of the RTO estimators for an endpoint SHOULD be kept as long as possible. If other state is kept for the endpoint (such as a DTLS connection), it is very strongly RECOMMENDED to keep the RTO state alive at least as long as this other state. In the absence of such other state, the RTO state SHOULD be kept at least long enough to avoid frequent returns to inappropriate initial values. For the default parameter set of [Section 4.8 of \[RFC7252\]](#), it is strongly RECOMMENDED to keep it for at least 255 s.

If an estimator has a value that is lower than 1 s, and it is left without further update for 16 times its current value, the RTO estimate is doubled. If an estimator has a value that is higher than 3 s, and it is left without further update for 4 times its current value, the RTO estimate is set to be

$$\text{RTO} := 1 \text{ s} + (0.5 * \text{RTO})$$

(Note that, instead of running a timer, it is possible to implement these RTO aging calculations cumulatively at the time the estimator is used next.)

Pseudocode and examples for the aging mechanism presented are available in [Appendix B.2](#) and in [Appendix C.2](#).

5. Advanced CoAP Congestion Control: Non-Confirmables

A CoAP endpoint MUST NOT send non-confirmables to another CoAP endpoint at a rate higher than defined by this document. Independent of any congestion control mechanisms, a CoAP endpoint can always send non-confirmables if their rate does not exceed 1 B/s.

Non-confirmables that form part of exchanges are governed by the rules for exchanges.

Non-confirmables outside exchanges (e.g., [RFC7641] notifications sent as non-confirmables) are governed by the following rules:

1. Of any 16 consecutive messages towards this endpoint that aren't responses or acknowledgments, at least 2 of the messages must be confirmable.
2. An RTO as specified in Section 4 must be used for confirmable messages.
3. The packet rate of non-confirmable messages cannot exceed $1/\text{RTO}$, where RTO is the overall RTO estimator value at the time the non-confirmable packet is sent.

5.1. Discussion

The mechanism defined above for non-confirmables is relatively conservative. More advanced versions of this algorithm could run a TFRC-style Loss Event Rate calculator [RFC5348] and apply the TCP equation to achieve a higher rate than $1/\text{RTO}$.

[RFC7641], Section 4.5.1, specifies that the rate of Non-Confirmables SHOULD NOT exceed $1/\text{RTT}$ on average, if the server can maintain an RTT estimate for a client. CoCoA limits the packet rate of Non-Confirmables in this situation to $1/\text{RTO}$. Assuming that the RTO estimation in CoCoA works as expected, $\text{RTO}[k]$ should be slightly greater than the $\text{RTT}[k]$, thus CoCoA would be more conservative. The expectation therefore is that complying with the NON rate set by CoCoA leads to complying with [RFC7641].

6. IANA Considerations

This document makes no requirements on IANA. (This section to be removed by RFC editor.)

7. Security Considerations

The security considerations of, e.g., [RFC5681], [RFC2914], and [RFC8085] apply. Some issues are already discussed in the security considerations of [RFC7252].

If a malicious node manages to prevent the delivery of some packets, a consequence will be an RTO increase, which will further reduce network performance. Note that this type of attack is not specific for CoCoA (and not even specific for CoAP), and many congestion control algorithms increase the RTO upon packet loss detection. While it is hard to prevent radio jamming, some mitigation for other forms of this type of attack is provided by network access control techniques. Also, the weak estimator in CoCoA increases the chances of obtaining RTT measurements in the presence of heavy packet losses, allowing to keep the RTO updated, which in turn allows recovery from a jamming attack in reasonable time.

8. References

8.1. Normative References

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Appendix A. Supporting evidence

(Editor's note: The references local to this appendix may need to be merged with those from the specification proper, depending on the discretion of the RFC editor.)

CoCoA has been evaluated by means of simulation and experimentation in diverse scenarios comprising different link layer technologies, network topologies, traffic patterns and device classes. The main overall evaluation result is that CoCoA consistently delivers a performance which is better than, or at least similar to, that of default CoAP congestion control. While the latter is insensitive to network conditions, CoCoA is adaptive and makes good use of RTT samples.

It has been shown over real GPRS and IEEE 802.15.4 mesh network testbeds that in these settings, in comparison to default CoAP, CoCoA increases throughput and reduces the time it takes for a network to process traffic bursts, while not sacrificing fairness. In contrast, other RTT-sensitive approaches such as Linux-RTO or Peak-Hopper-RTO may be too simple or do not adapt well to IoT scenarios, underperforming default CoAP under certain conditions [1]. On the other hand, CoCoA has been found to reduce latency in GPRS and WiFi setups, compared with default CoAP [2].

CoCoA performance has also been evaluated for non-confirmable traffic over emulated GPRS/UMTS links and over a real IEEE 802.15.4 mesh testbed. Results show that since CoCoA is adaptive, it yields better packet delivery ratio than default CoAP (which does not apply congestion control to non-confirmable messages) or Observe (which introduces congestion control that is not adaptive to network conditions) [3, 4].

A.1. Older versions of the draft and improvement

CoCoA has evolved since its initial draft version. Its core has remained mostly stable since [draft-bormann-core-cocoa-02](#). The evolution of CoCoA has been driven by research work. This process, including evaluations of early versions of CoCoA, as well as improvement proposals that were finally incorporated in CoCoA, is reflected in published works [5-10].

A.2. References

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Appendix B. Pseudocode

B.1. Updating the RTO estimator

```
// Default values
ALPHA = 0.125 // RFC 6298
BETA = 0.25 // RFC 6298
W_STRONG = 0.5
W_WEAK = 0.25

updateRTO(retransmissions, RTT) {
  if (retransmissions == 0) {
    RTTVAR_strong = (1 - BETA) * RTTVAR_strong
                  + BETA * (RTT_strong - RTT);
    RTT_strong = (1 - ALPHA) * RTT_strong + ALPHA * RTT;
    E_strong = RTT_strong + 4 * RTTVAR_strong;
    RTO = W_STRONG * E_strong + (1 - W_STRONG) * RTO;
  } else if (retransmissions <= 2) {
    RTTVAR_weak = (1 - BETA) * RTTVAR_weak
                 + BETA * (RTT_weak - RTT);
    RTT_weak = (1 - ALPHA) * RTT_weak + ALPHA * RTT;
    E_weak = RTT_weak + 1 * RTTVAR_weak;
    RTO = W_WEAK * E_weak + (1 - W_WEAK) * RTO;
  }
}
```

B.2. RTO aging

```
checkAging() {
  clock_time difference = getCurrentTime() - lastUpdatedTime;

  if ((RTO < 1s) && (difference > (16 * RTO))) {
    RTO = 2 * RTO;
    lastUpdatedTime = getCurrentTime();
  } else if ((RTO > 3s) && (difference > (4 * RTO))) {
    RTO = 1s + 0.5 * RTO;
    lastUpdatedTime = getCurrentTime();
  }
}
```

B.3. Variable Backoff Factor

```
backOffRTO() {
  if (RTO < 1s) {
    RTO = RTO * 3;
  } else if (RTO > 3s) {
    RTO = RTO * 1.5;
  } else {
    RTO = RTO * 2;
  }
}
```

Appendix C. Examples

C.1. Example A.1: weak RTTs

A large network of sensor nodes that report periodical measurements is operating normally, without congestion. The nodes transmit their sensor readings via CON messages every 20 s in an asynchronous way towards a server located behind a gateway, obtaining strong RTT measurements (RTT 1.1 s, RTTVAR 0.1 s) that lead to the calculation of an RTO of 1.5 s (in average) in each node. In this mode of operation, no aging is applied, since the RTO is refreshed before the aging mechanism applies.

Suddenly, upon detection of a global event, the majority of sensor nodes start transmitting at a higher rate (every 5 s) to increase the resolution of the acquired data, which creates heavy congestion that leads to packet losses and an important increase of real RTT between the nodes and the server (RTT 2 s, RTTVAR 1 s). Due to the packet losses and spurious retransmissions (which can fuel congestion even more), many nodes are not able to update their RTO via strong RTT measurements, but they are able to obtain weak RTT measurements. A node with an initial RTO of 1.5 s would run into a retransmission, before obtaining an ACK (given the RTT of 2 s and that the ACK is not lost).

This weak RTT measurement would increase the overall RTO of the node to 1.875 s ($\text{RTO} = 0.25 * 3 \text{ s} + 0.75 * 1.5 \text{ s}$). Following the same calculus (and RTT/RTTVAR values), after obtaining another weak RTT, the RTO would increase to 2.156 s. At this point, the benefits of the weak RTT measurements are twofold:

1. Further spurious retransmissions are avoided as the RTO has increased above the real RTT.
2. The increase of RTOs across the whole network reduces the rate with which retransmissions are generated, decreasing the network congestion (which leads to an RTT and packet loss decrease).

C.2. Example A.2: VBF and aging

Assuming that the frequency of message generation is even higher (every 3 s) and the real RTT would further increase due to congestion, the RTO at some point would increase to 4 s. Since now the RTO is above 3 s, no longer a binary backoff is used to avoid the RTO growing too much in case of retransmissions. As the generation of data from the nodes ceases at some point (the network returns to a normal state), the aging mechanism would reduce the RTO automatically

(with an RTO of 4 s, after 16 s the RTO would be shifted to 3 s before a new RTT is measured).

C.3. Example B: VBF and aging

A network of nodes connected over 4G with an Internet service is calculating very small RTO values (0.3 s) and the nodes are transmitting CON messages every 1 s. Suddenly, the connection quality gets worse and the nodes switch to a more stable, yet slower connection via GPRS. As a result of this change, the nodes run into retransmissions, as the real RTT has increased above the calculated RTO.

Since the RTO is below 1 s, the Variable Backoff Factor increases the backoff values quickly to avoid spurious retransmissions (0.9 s first retry, 2.7 s second retry, etc.). Further, if due to the packet losses and increased delays in the network no new RTT measurements are obtained, the aging mechanism automatically increases the RTO (doubling it) after 3.8 s ($16 * 0.3$ s) to adapt better to the sudden changes of network conditions. Without the Variable Backoff Factor and the aging mechanism, the number of spurious retransmissions would be much higher and the RTO would be corrected more slowly.

Appendix D. Analysis: difference between strong and weak estimators

This section analyzes the difference between the strong and weak RTO estimators. If there is no congestion, assume a static RTT of R' . Then, $E_strong_$ can be expressed as:

$$E_strong_ = R' + G,$$

since RTTVAR is reduced constantly by $RTTVAR = RTTVAR * 3/4$ (according to [RFC6298], and $SRTT=R'$), G would be dominant term in the $\max(G, K * RTTVAR)$ expression in the long run.

For the weak estimator: assume that the RTO setting converges to $E_strong_$ calculated above in the long run. If there is a packet loss, and an RTT is obtained for the first retransmission, then the weak RTT sample obtained by the weak estimator is:

$$RW' = R' + G + R'$$

Therefore, $E_weak_$ can be expressed as:

$$E_weak_ = RW' + \max(G, RW'/2) = 3 * R'$$

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