1 The Coexistence Problem

L4S flows are designed to fall-back to Reno-friendly behaviour on a loss. So if L4S [DSBET19] and classic [RFB01] flows coexist within the same queue, they will compete on equal terms as long as the queue does not support ECN marking.

If the queue does support ECN, whether with per-flow queuing (FQ[+18]) or a DualQ Coupled AQM [DSBET19], either ensures that L4S and classic flows coexist. However, with a classic ECN [RFB01] AQM in a single shared queue, L4S congestion controls (CCs) raise the ECN marking rate such that classic flows yield to them. Classic flows do not actually starve, but they reduce to a rate that can be 4–16 times less than the L4S flows (Figure 1).

![Figure 1: Quantification of the Rate Imbalance Problem between L4S and Classic ECN flows in a Classic ECN Queue](image)

The IETF’s Prague L4S Requirements [DSBET19] expect an L4S congestion control to somehow detect the presence of a classic ECN AQM at the bottleneck and fall back to Reno-friendly behaviour (as they do on a loss). This paper discusses how best to address that requirement.

2 Secondary Requirements

Beyond solving the coexistence problem, the following secondary requirements are proposed:
1. Rather than fall-back being a binary switch between modes, it should be a gradual changeover, the more certain it is that the AQM supports classic ECN;

2. Nonetheless, at either end of the spectrum of (un)certainty, there should be ranges where the CC behaves on the one hand purely scalably and on the other purely classically;

3. Minimal additional persistent TCP state;

4. The code should be structured with detection separate from changeover of behaviour, so that detection can eventually apply to more than one CC, while changeover is likely to be CC-specific;

5. However, until the concept is proven, it will be OK to initially implement the whole algorithm within the TCP Prague CC module, and only rationalize it once mature.

3 Code Structure

To simplify pseudocode, a float called $c$ controls how much the CC should behave as classic, from 0 (scalable) to 1 (classic). In practice this might be an integer variable `classic_ecn` in the range 0 to `CLASSIC_ECN`.

The `classic_ecn` indicator can continue beyond either end of this range, as tabulated below, in order to implement a degree of hysteresis where the CC algo behaves purely as L4S or purely classically.

| -L_STICKY ≤ classic_ecn ≤ 0 | Pure L4S behaviour |
| 0 ≤ classic_ecn ≤ CLASSIC_ECN | Transition between L4S and classic |
| CLASSIC_ECN ≤ classic_ecn ≤ C_STICKY | Pure classic behaviour |

It is up to the detection algo, not the CC algo, to maintain the `classic_ecn` variable. However, any particular CC algo can override the default parameters of the detection algorithm. For instance, a CC module could alter how 'sticky' the hysteresis is at either end by overriding the default L_STICKY and/or C_STICKY parameters.

Below, both passive and active detection mechanisms are proposed, both of which depend on each other and combine to pull and push the `classic_ecn` variable between its extremes. After experimentation with both active and passive detection, a solution might be found without only one of them.

4 Passive Detection of Classic ECN AQMs

The following metrics are likely to be relevant when detecting a classic ECN AQM:

- The onset of CE marking;
- Application-limited (no buffering at the sender);
- Receive window limited ($rwnd < cwnd$);
- The moving mean deviation, $\text{mdev}^1$ of the RTT.
- The difference between the smoothed RTT and a minimum RTT, with suitable safeguards against a false minimum and against step changes;

---

1 An alternative to standard deviation that is a little easier to compute and no less valid as a variability metric [JK88, Appx A]
4.1 Dependence on Presence of CE marking

Obviously no transition to classic should occur unless there has been a CE mark. Any transition should be suppressed for a number of RTTs after the onset of CE marking, both to allow the connection to stabilize and because aggressive competition for bandwidth is not a great concern with short flows. Indeed when fairness is considered over time, it is more fair for long-running flows to be less aggressive than short flows [GM02, Sd02, ZTH04, MSSM12, BCC+15, Bri19]—though a delay is motivated by a stabilization period rather than any desire to use a different form of fairness.

How long for instability to end? A classical slow-start ends on the first CE (unless it had already ended due to a loss). In the next few rounds, all the flows suffer a period of instability as they recover from the transient overshoot of the new flow. The random nature of this period leaves them all at different shares of capacity. Then they might take a few hundred further round trips to converge on stable shares. It is likely that any flow-start approach developed for shallow threshold ECN might have a less clear cut transition between a flow-start phase and a period of convergence. Given this likely heterogeneity in approaches to flow-start, it is not feasible to quantify how long any single flow should wait after the first CE before starting to detect a classic ECN AQM, because the period of instability depends more on the behaviour of other flows than its own.

Therefore it is proposed to start maintaining metrics as soon as the first feedback of a CE mark arrives, rather than attempting to wait for the subsequent instability to subside. As will be seen next, even if the RTT metrics start during this period of instability, they will have plenty of time to stabilize before they alter the CC behaviour.

How long before inappropriate convergence becomes significant? Convergence has still been described as ‘short’ [HRX08] if it takes one or two hundred rounds (if the flows even last that long). Therefore, relative to overall convergence time, it will be insignificant if a flow takes a couple of dozen rounds to work out whether it should be converging to an L4S or to a classic target.

Rather than take an absolute number of rounds before the CC behaviour starts to transition, it would better to depend on how strongly the other metrics are indicating that a transition is necessary. For instance, the higher RTT variance is, the fewer rounds would need to elapse before allowing a transition to start.

If CE marking stops for a protracted period, it will be likely that a non-ECN link has become the bottleneck. Then the choice between classic and scalable ECN behaviour would be moot and the default loss response would be sufficient. If CE marking picks up again later, it would be best to ignore (i.e. not measure) any period without CE marking and allow the other metrics to determine CC behaviour.

4.2 Dependence on being Self-Limited

If a TCP Prague flow is app-limited or receive-window limited (i.e. self-limited), there is no great need to fall-back to classic behaviour on receipt of an ECN mark.

The presence of CE marks while the flow is not trying to fill the pipe (its send buffer is empty) probably implies that a greedy flow or other short flows are sharing the link. Then (assuming cwnd validation is being used) the flow will not be increasing cwnd as much as competing traffic could be. In that case, a large classic response to a CE-mark could under-utilize the link until cwnd returned. So a small scalable response would be more appropriate.

Also, any tendency towards classic behaviour due to RTT variability (see below) will be more due to other flows. So the classic ECN variable ought to reduce by a certain amount per RTT while a sender is self-limited. However, not being self-limited alone is not a reason to increase the variable—for that there has to be a positive sign of a classic ECN AQM, such as RTT variability.

Similarly, while the sender is idle, any previous detection of a classic ECN bottleneck could become stale. However, during an idle period there are no per-RTT events, so an adjustment to the classic ECN variable will have to be made at the restart of activity based on TCP’s idle timer.
4.3 Dependence on RTT Variability

A large degree of RTT variability is probably the surest way to detect a classic-ECN bottleneck. So, if accompanied by CE marking it is likely to imply a classic ECN AQM at the bottleneck. For the Internet, ‘large’ can be quantified as more than 4–6 ms of variability, given the target L4S delay will generally be 1 ms or less while the lowest target delay to which classic AQMs are recommended to be configured is about 5 ms. So any classic queue could vary from zero to slightly above that.

Pseudocode for dependence of classic ECN fall-back on RTT variability will be given in §4.5. But first, the following two subsections will discuss possible false positives and false negatives.

4.3.1 Non-queuing causes of RTT variability with an L4S bottleneck

- A reroute.
- Variability in Interrupt handling, processor scheduling and batched processing by the endpoints and by nodes on the path. It is assumed that the combined result of all these variations will be small compared to variability of a classic ECN queue. This assumption will need to be tested and parameters set accordingly.
- ...any others?

TCP already maintains a moving average of RTT and deviation of the RTT from this average. However, it does not filter out step changes in the base RTT (e.g. due to a reroute), which could cause the moving average to be temporarily ‘incorrect’ so that the mean deviation from this incorrect average temporarily expands (Figure 4). The pseudocode in Appendix A is intended to fill that gap.

4.3.2 Low RTT variability with a classic ECN bottleneck

RTT variability will not distinguish a classic ECN bottleneck in the following cases:

- A high degree of flow multiplexing at a shared-queue bottleneck with a classic ECN AQM. The averaging effect of large numbers of uncorrelated sawteeth causes the mean deviation of the RTT of \( N \) flows sharing a buffer to be about \( 1/\sqrt{N} \) of that of 1 flow, derived straightforwardly from the Central Limit Theorem [AKM04].
- ...any others?

Few networks are designed so that sharing at a link serving a large number of individual flows is controlled by the end-points, let alone with a classic ECN AQM at this link as well. Nonetheless, we will consider three cases where this could possibly occur:

**Commercial ISP’s access link with a shared-queue classic ECN AQM:** Invariably, the operator designs the network so that the bottleneck is in the access link allocated to each customer, the capacity of which is isolated from other customers using a scheduler. For the mean deviation of a flow to appear to be 5× lower (e.g. 1 ms rather than 5 ms), at least 25 classic flows would have to be multiplexed together, by the Central Limit formula above. Such a scenario can occur within a single customer’s access. However, for the fall-back algorithms of each flow to be fooled into thinking the bottleneck was L4S, that many classic flows would all have to run continually with no disruption from other flows. We have to accept that the algorithm could give a false negative in such a scenario, which is unlikely but possible.

**Commercial ISP’s core or peering link with a shared-queue classic ECN AQM:** The bottleneck can sometimes shift to a core link or more likely a peering point, where flow multiplexing will be high enough to keep RTT very smooth. Usually this occurs during some sort of anomalous conditions, e.g. a provisioning mistake, a core link failure or a DDoS attack. If it does, the concern is that L4S flows could out-compete classic flows. Nonetheless, the scope for a high degree of flow rate inequality is very limited, as explained in Appendix B.
Campus network access link: A corporate or University network is rarely designed with an individual bottleneck for each user. Rather, each user typically has high speed connectivity to the campus (e.g. 1Gb/s Ethernet) and all stations using the Internet at any one time bottleneck at the campus access link(s) from the Internet. In such an access link, L4S flows will not coexist well with classic flows (as in Figure 1). It is not known whether any campus networks use classic ECN AQM in their access link, but they might do. Until the operator of such an AQM can deploy an L4S AQM, an unsatisfactory work-round would be to reconfigure the AQM to treat ECT(1) as Not-ECT so that it uses drop not CE as a signal for L4S flows. However, this would disincentivize L4S deployment. The alternative of just allowing the unfairness would also be an option, given applications already open multiple flows to achieve a similar advantage.

4.4 Dependence on Minimum RTT

Minimum RTT metrics are known to be problematic, especially where the buffer is already filled by other traffic before a flow arrives. Therefore, it may be preferable not to use this metric at all, and rely solely on RTT variability.

Nonetheless, it would do no harm to use a min RTT metric, as long as the outcome was asymmetric. In other words, a large difference between srtt and srtt_min would make classic fall-back more likely, while a small difference would not make classic fall-back less likely. This is the approach taken in the pseudocode.

4.5 Passive Detection Pseudocode

The following pseudocode pulls together all the passive detection ideas in the preceding sections.

```c
// Parameters
#define V ? // Weight of queue *V*ariability metric
#define D ? // Weight of mean queue *D*epth metric
#define S ? // Weight of *S*elf-limiting metric
#define C_FRAC_IDLE 2 // Multiplicative reduction in classic_ecn each idle timeout
#define L_STICKY 12*V // L4S hysteresis incl. min rounds from CE onset to transition
#define C_STICKY 12*V // Classic hysteresis
#define V0 4 // Reference queue *V*ariability [ms]
#define D0 4 // Reference queue *D*epth [ms]
#define srtt_min; // Already provided by Linux (suitably modified if SRTT is from Appx A)
#define classic_ecn; // Signed integer. The more +ve, the more likely it’s a classic ECN AQM
#define v; // The mean deviation of the RTT, same as MDEV in Appx A
#define d; // (SRTT - srtt_min), the likely mean depth of the queue.
#define s; // Proportion of the latest RTT that was self- (app- or rwnd-) limited
#define delta; // A temp variable to improve readability

// SRTT & MDEV: Smoothed RTT & Mean Deviation, either as already in Linux or Appx A

{ // On connection initialization
    classic_ecn = -L_STICKY;
}

{ // On CE feedback, enable delta calc’n if classic_ecn is clamped at its minimum
    classic_ecn += (classic_ecn <= -L_STICKY);
}

{ // On expiry of idle timer
    if (classic_ecn > 0) {
        classic_ecn = classic_ecn/C_FRAC_IDLE;
    }
}
```

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re-arm_idle_timer();
}

if (classic_ecn > -L_STICKY) { // Suppress delta calc’n if classic_ecn at min
delta = V*lg(v/V0) + D*lg(max(d/D0, 1)) - S*s;
classic_ecn = min(max(classic_ecn + delta, -L_STICKY), C_STICKY);
} else {
    ect_tracers = 0; // Unsuspend ect_tracers (for active detection in Section 5)
}

4.5.1 Passive Detection Pseudocode Walk-Through

While classic_ecn sits at -L_STICKY, calculation of delta, the change in classic_ecn, is suppressed to save unnecessary processing. Maintenance of the variables used in this calculation (not shown) could also be suppressed.

At connection initialization, maintenance of the classic_ecn variable starts off in this quiescent state. Feedback of a CE mark awakens it by incrementing classic_ecn by its minimum integer granularity (1).

Every RTT, as long as classic_ecn is not in its quiescent state, the per-RTT change in classic_ecn is calculated. This is the core of the passive classic ECN detection algorithm. To make the pseudocode more readable, a temporary variable (delta) is assigned to this intermediate calculation.

The change in classic_ecn consists of three terms, each weighted relative to each other by the three parameters V, D and S:

RTT Variability, v (§ 4.3): The metric 1g(v/V0) is used, where lg() is an approximate (fast) base-2 log and V0 is a reference mean-deviation parameter (default 4 ms). It is increasingly hard to achieve smaller deviations, so it is necessary to use a log function in order to ensure that a mean deviation of, say, 500 µs moves the classic ECN variable as much downwards as a mean deviation of 32 ms moves it upwards (respectively 8 times smaller and 8 times larger than V0 = 4 ms).

Likely Mean Queue Depth, d (§ 4.4: The metric lg(max(d/D0), 1) uses the log of the ratio of d over the reference queue depth D0 for the same reason as the previous bullet. However, the max() with respect to 1 ensures it ignores small queue depths, which could be suspect, as explained in § 4.4.

Self-Limitation, s (§ 4.2): Here the fraction of the RTT that was self-limited can be used directly.

The first two terms both involve a log function, so in practice, with judicious choice of the parameters V and D, they could be combined efficiently. For instance, if V/D=2, then

\[ V*lg(v/V0) + D*lg(max(d/D0,1)) \]

is equivalent to

\[ ( d>D0 \ ? \ D \ * \ lg(v^2*d/(V0^2*D0)) \ : \ V*lg(v/V0) ) \]

The last two variables can each only push classic_ecn in one direction. Mean queue depth can only push it upwards (more classic), while self-limitation can only push it downwards (less classic). If mean queue depth is below the reference queue depth D0, or there is no self-limitation in a round, the classic_ecn indicator remains unchanged.

If, on balance, the calculations to detect classic ECN AQM are positive, delta increases classic_ecn towards its maximum (C_STICKY). But if they are negative, delta decreases classic_ecn towards its minimum (-L_STICKY) where further calculations will be suppressed, at least until calculations are reawakened by the next CE mark.

During an idle period, classic_ecn is exponentially reduced by default to 1/2 of its previous value on every expiry of the idle timer, but only if it is positive. Thus, while idling, a connection that had
detected a classic ECN AQM will gradually drift to the L4S end of the transition, but towards the cusp of the transition. Then, if it continues to detect a classic ECN AQM once it restarts, it will immediately transition to classic ECN mode again, while it is restarting.

4.6 Questioning Assumptions used for Passive Detection

4.6.1 Clocking Interval

So far, it has been assumed that classic.ecn should be recalculated once per RTT, for all the detection metrics except idling time. This question needs to be addressed explicitly.

Four potential intervals on which to clock changes are:

- round trips
- absolute time intervals
- after a certain amount of sent packets, or even sent bytes
- after a certain amount of feedback (ACK counting).

**Stabilization and convergence:** It makes sense to count how long to wait for a connection to stabilize and converge in round trips, because each flow adjusts iteratively on a round trip timescale.

**RTT variability:** There is an argument that changes to classic.ecn due to RTT variability should be clocked on a count of the ACKs received, e.g. every 32 or every 64 ACKs. This is because the precision of round trip smoothing and measurements of mean deviation depends on how many ACKs have contributed to the average. However, the variability of the queue itself alters dependent on evolution of each flow’s congestion window, which adjusts on a round trip timescale. Therefore dependence of the value of classic.ecn on RTT variability metrics should be clocked against round trips.

**Self-limitation:** Self-limitation is measured as a proportion, so it does not matter whether it is a proportion of a round, a proportion of a certain time period, or a proportion of any other metric. Given other metrics should be clocked on round trips, it makes sense to clock self-limitation calculations on the same events.

**Idling:** There is no basis to argue that changes to classic.ecn due to idling should be clocked on any particular metric. Nonetheless, the only metric that continues to clock during an idle period is time, so this is the only practical metric to use.

Counting either in sent packets or absolute time would be easy to implement, but neither seem to have any logical backing, for any of the metrics.

4.7 Parameter settings

Currently, the parameters given in the pseudocode are guesses. These can be used as initial values in evaluation experiments. Once a full set of values is found empirically (assuming the algorithm even works at all), it may be possible to optimize the code, e.g. by combining the two log calculations into one.
5 Active Detection of Classic ECN AQMs

5.1 Active Detection: Problem

One can imagine a number of naïve active measures that a sender could take to determine with much greater certainty whether the bottleneck is L4S or classic:

- The sender could duplicate a small proportion of ECT1 packets and set them as ECT0.
- The sender could set a small proportion of packets to ECT0 instead of ECT1;

The intent here would be to measure whether the delay of ECT0 packet tends to be greater than ECT1 packets. We shall call these 'ECT tracer' packets, because they trace whether the ECT field causes a packet to be classified into a different queue. However, if the receiver was using delayed ACKs (most do), it would confound these naïve approaches:

- in the first case, even if both duplicates were acknowledged (the first to arrive might not be), the sender would not be able to tell from the acknowledgement(s) which duplicate had arrived first.
- In the second case, some ECT0 packets would not trigger an ACK so their delay could not be measured. Also, if the bottleneck were an L4S DualQ Coupled AQM, any queuing delay suffered by the ECT0 packets would hold back the connection, and some might be delayed enough relative to ECT1 packets to make TCP believe they had been lost, causing the sender to spuriously retransmit and spuriously reduce its congestion window.

5.2 Active Detection: Solution

A better strategy would be:

- for the sender to make the receiver override its delayed ACK mechanism by ensuring that at least part of both tracer packets duplicate bytes already sent. This is because standard TCP congestion control [APB09, APS99] recommends that a receiver sends an immediate ACK in response to duplicate data to expedite the fast retransmit process, and this recommendation has stood since the first Internet host requirements in 1989 [Bra89].

- for either tracer packet to push forward the acknowledgement counter, so that the sender can tell which probably arrived first (there can be no certainty, because ACKs can be reordered).

The best sender-only strategy so far conceived would be as follows (also illustrated in Figure 3):

1. If the classic.ecn indicator is approaching the transition range from below, i.e. negative but close to zero, for a small proportion of segments send instead the following three smaller packets, all back-to-back:
   - a larger front segment marked ECT1;
   - a smaller middle segment marked ECT0, duplicating at least the last 2 B of the first segment;
   - a rear segment marked ECT1 of the same size as the second but only duplicating the last byte of the first segment;

2. If the ACK for the middle tracer arrives after that for the rear tracer, the AQM is likely to be L4S (unless some other mechanism happens to have coincidentally re-ordered the packet stream at this point);
Figure 2: Tracer packets to detect separate treatment of ECT1 packets

Note that the ECT0-marked packet only includes redundant bytes, so if it is delayed (or dropped) by a classic queue, it does not degrade the L4S service.

The combined size of all three packets should be no greater than 1 MTU so that, if packet pacing is enabled, all three packets will remain back-to-back without having to alter pacing (also the two back-to-back ECT1 packets will cause no more of a burst in an L4S queue than a single packet would).

The front packet is larger to reduce the risk that detection of L4S AQMs will sometimes fail. Being larger, it is more likely to still be dequeuing when the rear packet arrives at the bottleneck. Otherwise, if there was a DualQ Coupled AQM at the bottleneck, and if there was no other classic traffic queued ahead of the middle tracer, it could start dequeuing after the front packet had dequeued, but before the rear tracer arrived.

Nonetheless, in order to minimize the possibility that the small tracer packets are treated differently by middleboxes, they should be larger than the size $S$ of the largest packet that might be considered 'small' by common acceleration devices ($S = 98$ B would probably be sufficient).

### 5.3 Active Detection Pseudocode

The following pseudocode implements the active detection ideas in §5. It uses some of the macros and variables defined in the passive detection pseudocode above.

```plaintext
// Parameters
#define TRACER_NUM 4 // Number of sets of 3 active tracers to send
#define REAR_SIZE 98 // Min size of middle and rear tracers [B]

ect_tracers = 0; // Unsigned int storing remaining tracers (-ve means disarm sending)
tracer_nxt = 0; // Point in the sequence space after the most recently sent tracer
    // special (tracer_nxt == 0) disables checking for tracer ACKs

// Functions
send_tracer(start, size, ecn); // Sends ECT tracer seg from 'start' in send buffer

// The following statements are intended to be inserted at the stated events

{ // Per RTT
    if (classic_ecn >= -L_STICKY/TRACER_NUM & !ect_tracers) {
        ect_tracers = TRACER_NUM;
    }

    if (ect_tracers < 0) // The tracer armed 1RTT ago has been sent
        ect_tracers *= -1; // Arm sending of the next tracer
}

{ // Prior to sending a packet
    if (ect_tracers > 0 & snd_q >= smss) {
        front_size = smss - 2 * (sizeof_tcp_ip_headers() + REAR_SIZE);

2 Unless AccECN TCP feedback with the TCP Option was implemented and it successfully traversed the path, but that is too unlikely to rely on
```
send_tracer(snd.nxt, front_size, ECT1); // Front tracer
send_tracer(snd.nxt - 2, REAR_SIZE, ECT0); // Middle tracer
send_tracer(snd.nxt - REAR_SIZE + 1, REAR_SIZE, ECT1); // Rear tracer
tracer_nxt = snd.nxt;
if (--ect_tracers) {
    ect_tracers *= -1; // Negate to disarm sending of the next tracer
} else if (classic_ecn >= -L_STICKY/TRACER_NUM) {
    ect_tracers -= TRACER_NUM + 1; // Suppress further tracers
}
}

{ // On receipt of seg (pure ACK or data)
    if (tracer_nxt) {
        if (rcv.nxt == tracer_nxt && seg.sack == tracer_nxt - 1)
            // middle arrived after rear, so probably L4S bottleneck
            classic_ecn = max(classic_ecn - L_STICKY/TRACER_NUM, -L_STICKY);
        if (ect_tracers == -TRACER_NUM - 1) // Further ECT tracers have been suppressed
            tracer_nxt = FALSE; // Suppress further ACK checking
    }
}

5.3.1 Active Detection Pseudocode Walk-Through

Interaction between Active Testing and the classic_ecn Indicator: Greater RTT variability might imply either a classic bottleneck or an L4S bottleneck combined with variability from another link (e.g. non-L4S WiFi). Whereas low variability is more likely to imply an L4S bottleneck. Therefore if the result of an active test is L4S, it pushes the classic_ecn indicator towards the L4S end, counteracting the opposite trend due to variability. Whereas if the result of an active test is classic, it does not need to alter classic_ecn; it can leave variability to do that.

Active detection is more decisive, but it alters the normal transmission pattern. So to avoid unnecessarily altering the sending pattern, passive measurement alone is used first to determine whether active measurement is worthwhile.

if active measurement proves necessary, the plan then is to send a small number (default TRACER_NUM = 4) of sets of three tracer packets. If any set of tracers detects that an L4S AQM is likely, it moves the classic_ecn indicator towards the L4S end of the spectrum by an amount L_STICKY/TRACER_NUM.

Thus if all 4 tests detect L4S, classic_ecn reduces by L_STICKY. The tests start at classic_ecn >= -L_STICKY/4, so if all 4 tests detect L4S, it will return to its floor value of -L_STICKY, and the CC will never have behaved as anything other than pure L4S. Bear in mind that the classic_ecn indicator will still be altered by the passive detection algorithm as well.

If, on the other hand, no set of tracers detects L4S, the active tests will not alter the classic_ecn indicator at all. Then, if the bottleneck is classic, continuing passive tests will detect the higher RTT variability and continue to push the classic_ecn indicator towards the classic end of the spectrum.

Between these two extremes, if not all the active tests detect L4S, the classic_ecn indicator will be pushed down less and stop short of its floor. Then if RTT variability continues, passive detection will more rapidly return it to the -L_STICKY/4 threshold where active tests resume.

State Variables To detect which tracer packet arrived first, it is necessary to store an indication of which feedback to check. Therefore no more than one set of tracers is sent per round trip, to minimize the per-connection state needed. This also spaces out the tracer tests, so that the small amount of redundant data each one sends hardly causes any inefficiency³.

³ With typical MTU and header sizes, a set of 3 tracer packets consumes 1 MTU, but sends about 12% less TCP data that would normally be in a full MTU. If there were say 16 packets per round, this inefficiency would be reduced to 12%/16 = 0.75%
Two additional state variables are needed for each connection:

- **ect_tracers**: This state variable stores the number of ECT tracers outstanding. Zero is not really a special value; it just has the expected meaning—that no tracers are outstanding.

- **tracer_nxt**: After a set of three tracer packets have been sent, tracer_nxt stores the next byte in the sequence space. Then later the matching ACKs for the tracers can be found. If the ACK never arrives, there is just no outcome to the test.

Negative values of ect_tracers are special; they store the number of outstanding sets of tracers but disarm them for a round trip (so that the feedback from the last one has time to return).

The negative value of ect_tracers one lower than -TRACER_NUM (-5 by default) is a further special value that suppresses all further tracers.

Tracers are not suppressed as long as the outcome after 4 tracers has reduced the classic_ecn indicator below the threshold at which active tests are triggered (-L_STICKY/4). Then, if the indicator rises to this threshold again, another set of tracers can be triggered. But, if the indicator has not reduced after the 4 tracer tests (i.e. all 4 tracer tests pass without reordering), all further active tests are suppressed so that continuing passive measurements are allowed to push the indicator upwards towards the classic ceiling (causing the CC to transition to classic behaviour).

If RTT variability reduces (e.g. because the bottleneck moves from a classic to an L4S AQM) such that the passive tests on their own pull the indicator down to the L4S floor, active tests suppression is removed by setting ect_tracers = 0.

**Per Packet Processing Efficiency**  
The special values of the variables ect_tracers and tracer_nxt are used to suppress the more complex conditions that would otherwise have to be checked per packet, respectively: whether each packet to be sent should be replaced by a set of tracers; and whether each ACK is feedback from a tracer.

For efficient implementation, rather than checking a flag variable on millions of packets just to send or receive a few packets differently, it might be better to somehow suppress regular packet sending, send the required number of tracer packets manually, then resume sending. This will need to be investigated during implementation.

### 6 CC Behaviour Changeover Algorithm

#### 6.1 DCTCP-Based Example

This example modifies DCTCP’s smallest congestion window reduction, by making it a function of alpha and c, where alpha is the EWMA of the congestion level. Two types of simple algorithm are conceivable. They are compared in the two alternative statements to calculate reduction following the original statement used by DCTCP in the pseudocode below:

```c
#define BETA_ABE 0.7 // ABE: Alternative Backoff with ECN [RFC8511]
#define ALPHA_ABE 2*(1-BETA_ABE) // 0.6

// For pseudocode clarity, c is a float covering the classic ECN transition (Section 3)
c = min(max(classic_ecn / CLASSIC_ECN}, 0), 1);

// original DCTCP reduction within prague_ssthresh()
reduction = cwnd * alpha / 2;

// reduction alternative #1
reduction = cwnd * (alpha + c * (ALPHA_ABE - alpha)) / 2;

// reduction alternative #2
reduction = cwnd * max(alpha, c * ALPHA_ABE) / 2;
```
The proposed changeover algorithm transitions its response to ECN from DCTCP-like to ABE-like as \( c \) transitions from 0 to 1.

Alternative Backoff with ECN (ABE) is an Experimental RFC [KWAF18] that suggests it is preferable for the reduction in cwnd to be less severe in response to an ECN signal than to a loss. The logic is that loss is more likely to emanate from a deep buffer, whereas any ECN signals are likely to be emanating from a modern AQM which will be configured with shallow target queuing delay. Therefore, it is reasonable to reduce less in response to ECN in order to improve utilization. A downside with ABE is that it will lead to ECN flows competing more aggressively with non-ECN flows, but the difference is not so great that non-ECN flows would be severely disadvantaged.

It is easiest for DCTCP to fall back to Reno (though falling back to a less lame congestion control such as Cubic or BBRv2 would be preferable). On an ECN signal, the ABE RFC recommends a reduction to \( \beta_{ecn} \) of the original cwnd, where for Reno \( \beta_{ecn} \) is in the range 0.7 to 0.85. The pseudocode above and the plots below use \( \beta_{ecn} = 0.7 \). If ABE were disabled, for Reno it would be appropriate to transition using \( \beta_{ecn} = \beta_{loss} = 0.5 \), but this detail is not shown in the pseudocode.

The macro \( \text{ALPHA}_{\text{ABE}} \) is just the value that, when halved, would limit the multiplicative reduction of cwnd to \( \text{BETA}_{\text{ABE}} \), by the formula: \( \text{reduction} = \text{cwnd} \times \text{BETA}_{\text{ABE}} = \text{cwnd} \times (1 - \text{ALPHA}_{\text{ABE}} / 2) \)

Figure 3 shows the CC reduction on a linear and log scale for the two alternative changeover algorithms. An example pattern of congestion marking is used to cause \( \alpha \) to vary while the \( c \) variable sweeps its range of values, including plateaus at 0 and 1.

Alt#1 gives the reduction a pro-rata contribution from each of \( \alpha \) and \( c \), dependent on the value of \( c \). Alt#2 takes the simple maximum of \( \alpha \) and the value of \( c \) scaled down by \( \text{ALPHA}_{\text{ABE}} \).

As flow rates scale, the typical value of \( \alpha \) becomes very small, so it is deceptive to focus on the rounds when \( \alpha \) is high. Nonetheless, in current networks \( \alpha \) can approach 100%. With either alternative, when \( \alpha \) is small, the log plots show that \( c \) dominates over most of its range. However, on the left of the log plot it can be seen that \( \alpha \) dominates when \( c \) is close to zero.

Alt#1 behaves more in the spirit of a transition, because it takes pro-rata contributions from each approach. Whereas Alt#2 is more like a binary switch-over. However, the difference is very subtle and unlikely to be noticeable by end-users.

Both alternatives can lead to a reduction greater than \( \text{APHA}_{\text{ABE}} \) (at about round #400 in Figure 3). This effect is less severe with Alt#1, but it not necessarily a bad thing to reduce cwnd by more than \( \text{APHA}_{\text{ABE}} \) when congestion is high.

Ultimately, the two alternatives are similar enough that the choice between them can be made on simplicity grounds, in which case Alt#2 is slightly preferable.
6.2 Transition of ECT marking?

When the CC transitions from scalable to classic, should the marking of packets transition from ECT1 to ECT0?

Let us consider a bottleneck with each type of AQM in turn:

**Classic AQM:** The only concern here is the sender’s CC behaviour, not its packet markings. If the CC does not transition to classic behaviour, it might outcompete classic flows (if the bottleneck is not FQ). But, it makes no difference whether the sender marks the packets ECT0 or ECT1. Because ‘classic’ means RFC 3168, and RFC 3168 requires an AQM to treat ECT0 and ECT1 identically.

**L4S AQM:** Here both the packet markings and the CC behaviour need to comply with the L4S spec. [DSBET19] in order to achieve any L4S performance benefit. If packets are not marked ECT1, they will never be classified into an L4S queue.

Therefore, it is not a good idea for an L4S-capable CC to transition packet markings to ECT1, even if it transitions to classic CC behaviour (because it detects a classic ECN bottleneck). It does no harm to anyone by marking its packets ECT1. But if it uses ECT0, then if the bottleneck moves to one that supports the L4S [DSBEAT19], its packets will be classified into the classic queue and it will never detect the lower delay variability that would trigger its transition back to L4S.

Note that a classic ECN-capable CC does not harm other flows in an L4S queue\(^4\); it just unnecessarily under-utilizes capacity on its own and competes lamely with L4S flows.

To summarize this section, a sender that is L4S-capable should always set its packets to ECT1, irrespective of whether it has transitioned to classic CC behaviour.

7 Acknowledgements

Transitioning gradually from scalable to classic behaviour and using ECT0 packets for active detection were based on initial ideas suggested by Koen De Schepper.

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References

[AKM04] Guido Appenzeller, Isaac Keslassy, and Nick McKeown. Sizing Router Buffers. *Proc. ACM SIGCOMM’04*, Computer Communication Review, 34(4), September 2004.

[APB09] M. Allman, V. Paxson, and E. Blanton. TCP Congestion Control. Request for Comments 5681, RFC Editor, September 2009.

[APS09] M. Allman, V. Paxson, and W. Stevens. TCP Congestion Control. Request for Comments 2581, RFC Editor, April 1999.

[BCC+15] Wei Bai, Li Chen, Kai Chen, Dongguan Han, Chen Tian, and Hao Wang. Information-Agnostic Flow Scheduling for Commodity Data Centers. In 12th USENIX Symposium on Networked Systems Design and Implementation (NSDI 15), pages 455–468, Oakland, CA, 2015. USENIX Association.

[Bra89] R. Braden. Requirements for Internet Hosts – Communication Layers. Request for Comments 2581, RFC Editor, October 1989.

[Bri19] Bob Briscoe. Per-Flow Scheduling and the End-to-End Argument. Discussion Paper TR-BB-2019-001, bobbriscoe.net, July 2019.

[DSBEAT19] Koen De Schepper, Bob Briscoe (Ed.), Olga Albisser, and Ing-Jyh Tsang. DualQ Coupled AQM for Low Latency, Low Loss and Scalable Throughput (L4S). Internet Draft draft-ietf-tsvwg-aqm-dualq-coupled-10, Internet Engineering Task Force, July 2019. (Work in Progress).

[DSBET19] Koen De Schepper, Bob Briscoe (Ed.), and Ing-Jyh Tsang. Identifying Modified Explicit Congestion Notification (ECN) Semantics for Ultra-Low Queuing Delay (L4S). Internet Draft draft-ietf-tsvwg-ecn-l4s-id-07, Internet Engineering Task Force, July 2019. (Work in Progress).

\(^4\) In contrast to a non-ECN-capable classic CC, which overruns the shallow ECN threshold until it detects tail drop
Figure 4: Plot of 'incorrect' and 'correct' smoothed RTT and mean deviation after a reroute

A Algorithm for Filtering Reroutes out of RTT Metrics

The following pseudocode results in variables for smoothed RTT and the mean deviation from it. It filters out any significant step change in the base RTT, e.g. due to a reroute, as visualized by the value of srtt[1] in Figure 4.

There is a valid concern that this algorithm might cause SRTT to incorrectly jump to a new smoothed RTT merely due to an episode of increased delay variability. To address this, it would not actually be necessary for TCP to use the newly provided values of SRTT and MDEV, except for classic ECN fall-back purposes. This might make the fall-back mechanism less sensitive, but that could be the developer’s intent.

// Macros
#define G1 1/8 // The gain already used by TCP to maintain srtt

5 In the Linux code, note that srtt holds the average RTT scaled up by 1/G1, and mdev holds the mean deviation of the RTT scaled up by 1/G2.
#define G2 1/4 // The gain already used by TCP to maintain mdev
#define MDEV_MAX 2*sizeof(mdev)-1 // Max value of mdev used to represent infinity
#define K1 1+G2*(K2*(1-G1)+(K2-1)*(1-G2)-1) // Hysteresis factor (see text later)
#define K2 2 // Outlier threshold, as multiple of mdev
#define SRTT (mdev[1] < mdev[0] ? srtt[1] : srtt[0]) // SRTT can be used wherever TCP uses srtt
#define MDEV (mdev[1] < mdev[0] ? mdev[1] : mdev[0]) // MDEV can be used wherever TCP uses mdev

// Definitions of variables and functions
mrtt; // Latest measured RTT
/* srtt[1] and mdev[1] are candidate alternatives to srtt[0] and mdev[0],
that TCP previously maintained (but not as array variables)
using functions with templates srtt(mrtt, srtt) and mdev(mrtt, mdev)
*/
srtt[2]; // Array for smoothed RTT (primary and alt)
mdev[2]; // Array for mean deviation of RTT (primary and alt)

if (srtt[1]) { // Update alternative srtt and mdev (order-significant)
mdev[1] += G2 * (abs(mrtt - srtt[1]) - mdev[1]));
srtt[1] += G1 * (mrtt - srtt[1]);
}

/* Check whether new measurement is an outlier wrt the primary RTT metrics
* before using it to update them
*/
if (abs(mrtt - srtt[0]) <= K2 * mdev[0]) { // Non-outlier
// suppress maintaining alt's if worse mean deviation
if (srtt[1] && (mdev[1] > mdev[0]))
srtt[1] = FALSE;
mdev[1] = MDEV_MAX;
} elif (!srtt[1]) { // Initial outlier
srtt[1] = mrtt;
mdev[1] = mdev[0] * K1; // Inflate by K1 for hysteresis
}

// TCP's usual update of srtt and mdev (order-significant)
mdev[0] += G2 * (abs(mrtt - srtt[0]) - mdev[0]));
srtt[0] += G1 * (mrtt - srtt[0]);

The gain parameters given (G1 and G2) are those used in current Linux. However, in the original
discussion of the setting of these parameters in Jacobson and Karels [JK88, Appx A] 1/G1 and 1/G2 were
recommended to be respectively a little greater and a little less than the congestion window, measured in
segments. However, the Linux code has never related these parameters to cwnd and they remain set as
they were when typical values of cwnd were hundreds of times lower than they are today. If these gain
values were greatly reduced, it would strengthen the need to filter out step changes in the base RTT.

The formula for the hysteresis factor, K1 needs an explanation. The value of

\[ 1 + G2 \times (K2 \times (1 - G1) + (K2 - 1) \times (1 - G2) - 1) \]

is intended to ensure that the alternative srtt will still not be preferred even if an outlier in the primary
measurement of RTT arrives followed by a measurement that is as close as possible to the first outlier
without actually being an outlier. Specifically, the first and second RTT measurements are taken as just
above and just below the outlier threshold (srtt[0] + K2 * mdev[0]) before either measurement is taken.
The derivation is left as an exercise for the reader.

---

6 Linux TCP uses a third gain value of 1/32 in the case where mrtt is less than the smoothed average AND its distance
from the average has increased. A comment in the code points to the Eifel algorithm as a possible rationale, but another
comment sarcastically says that the code implements the opposite of what was intended, without saying why it has not
been fixed.
B  ISP’s core or peering link with a shared-queue classic ECN AQM

First, for brevity, we will use the term common link for either a core link or a peering link.

Initially, let us assume that end systems all ensure equal flow rates at a bottleneck and let us define the equal division of a bottleneck’s capacity among all flows bottlenecked there as the 'equitable rate' for that bottleneck.

As the number of flows converging into a common link grows, let’s assume there comes a point where the sum of all the flows feeding traffic to it exceeds its capacity. If the number of flows continues to rise, the equitable rate for the common bottleneck continues to reduce. As the equitable rate reduces below the highest capacity access links, the bottleneck for any single flows in those access links moves to the common link.

Let us now imagine that the equitable rate has just reduced to 50% of the capacity of the fastest access link feeding the common bottleneck. If it contains one flow, that will now be running at half the access rate. If it contains two flows, the bottleneck for them will start to move to the common link as well.

Now let’s change the scenario by replacing some classic sources with L4S. At the common bottleneck, there will be little variability in the queue because of the high degree of multiplexing. So as the bottleneck moves there, L4S flows will not detect a classic ECN bottleneck and they will yield less than any classic flows. Classic flows will end up below the equitable rate and L4S flows above it. However, as L4S flows increase, they will bottleneck in their own access link again, which will naturally limit the inequality to 100%/50% = 2x.

Of course, serious anomalies might concentrate so much load at a common link that the equitable rate reduces to less than 50% of the fastest access, say x%. Then the worst inequality would be 100/xx. But it is extremely rare for an anomaly to even reduce x to 50%. In robustly designed networks, even during an anomaly, x will only just dip below 100%, e.g. 95%. Then the worst inequality due to classic ECN fall-back not detecting a classic ECN AQM in a highly multiplexed common link would be 100/95 = 1.05x.
# Document history

| Version | Date       | Author     | Details of change                                                                 |
|---------|------------|------------|-----------------------------------------------------------------------------------|
| 00A     | 20 Oct 2019| Bob Briscoe| First draft.                                                                       |
| 00B     | 21 Oct 2019| Bob Briscoe| Moved alt-srtt algo to appendix and made optional, also corrected K1 and used MDEV_MAX. Completed all the discussions about other factors. Just the pseudocode to pull it all together left to do. |
| 00C     | 23 Oct 2019| Bob Briscoe| First full draft. Completed pseudocode that pulls all the metrics together.         |
| 00D     | 02 Nov 2019| Bob Briscoe| Added active detection section. Other minor alterations.                            |
| 01      | 02 Nov 2019| Bob Briscoe| Issued as a complete design, but still some corners to investigate.                 |