Coupling Discrete Time Events to Continuous Time in RMCAT

(a.k.a. The Anatomy of a RMCAT RTT)

and Reasonable Bounds on the Time Rate
of Change in Available Capacity

Michael A. Ramalho, Ph.D.

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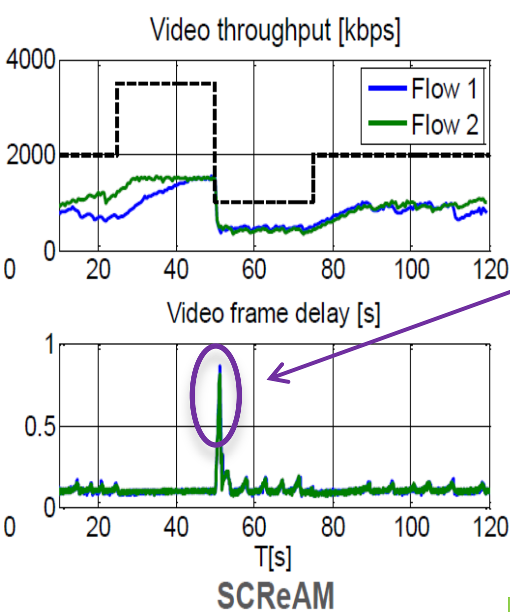
Talk Outline

1. Motivation (Prior Work On Test Plan Capacity Change Design)
2. RMCAT Discrete Time RTT Formalized
   - Fluid-flow (continuous-time) model and rigorous RMCAT RTT definition.
3. Infinitely Fast Capacity Change Downward
   - Unavoidable delay spike caused by infinitely fast capacity change
4. How Quickly ANY RMCAT Design Can Track Capacity Changes
   - Result is independent of algorithm type (“self-clocked” or “rate-based”).
5. Reasonable Assumptions on Time-Rate-of-Change of Capacity
   - Worse-case RTT defines “tracking responsiveness” (w/o predictive component).
   - Squelching mechanisms required (self-clocked schemes do this automatically).
   - TCP Dynamics as a function of their RTT.
   - A reasonable bound on RTCP feed back intervals.
6. Implications for Adaptation with Wireless (WiFi/LTE/etc).

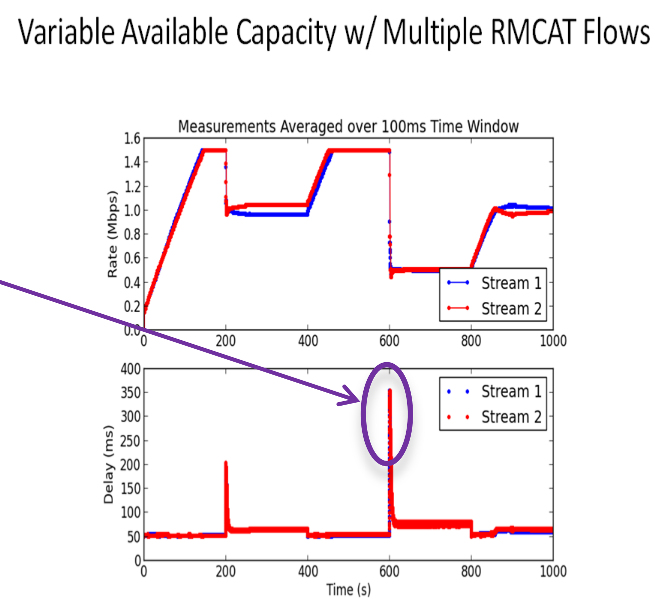
Motivation (Discussion at IETF 90)

Colin Perkins (Last Call on rmcat-cc-requirements):

- However, as I noted at IETF 90, I think the draft should also include a secondary requirement to **keep delay variation (jitter) down**, where possible, since larger delay variation needs larger receiver-side buffers to compensate, increasing overall latency.



Large Delay Spikes

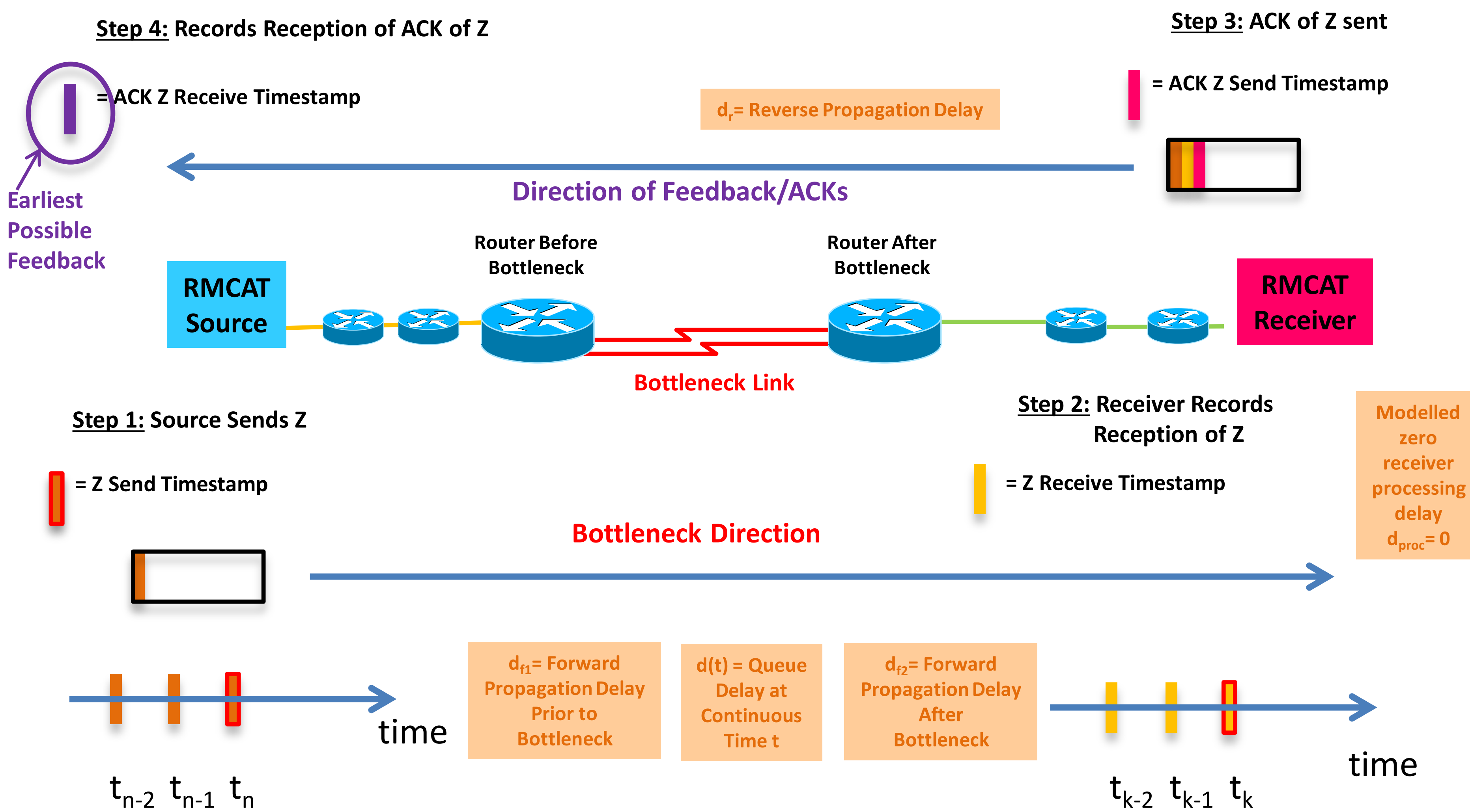


Colin (and others) believed these might be artifacts of the algorithms

NADAv2

A RMCAT Lab Discrete Time RTT (for Seq. No. = Z)

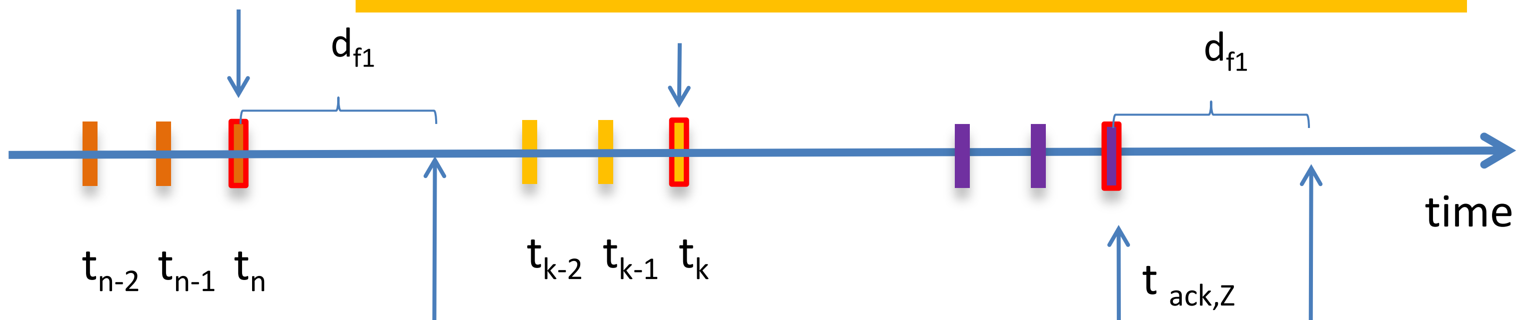
Note: Per-packet Feedback (no RTCP yet)



RMCAT LAB: Measurement Framework (Seq. No. = Z)

Sequence number Z sent.

Sequence number Z received (forward delay calculated here).



Sequence number Z-1 sent.

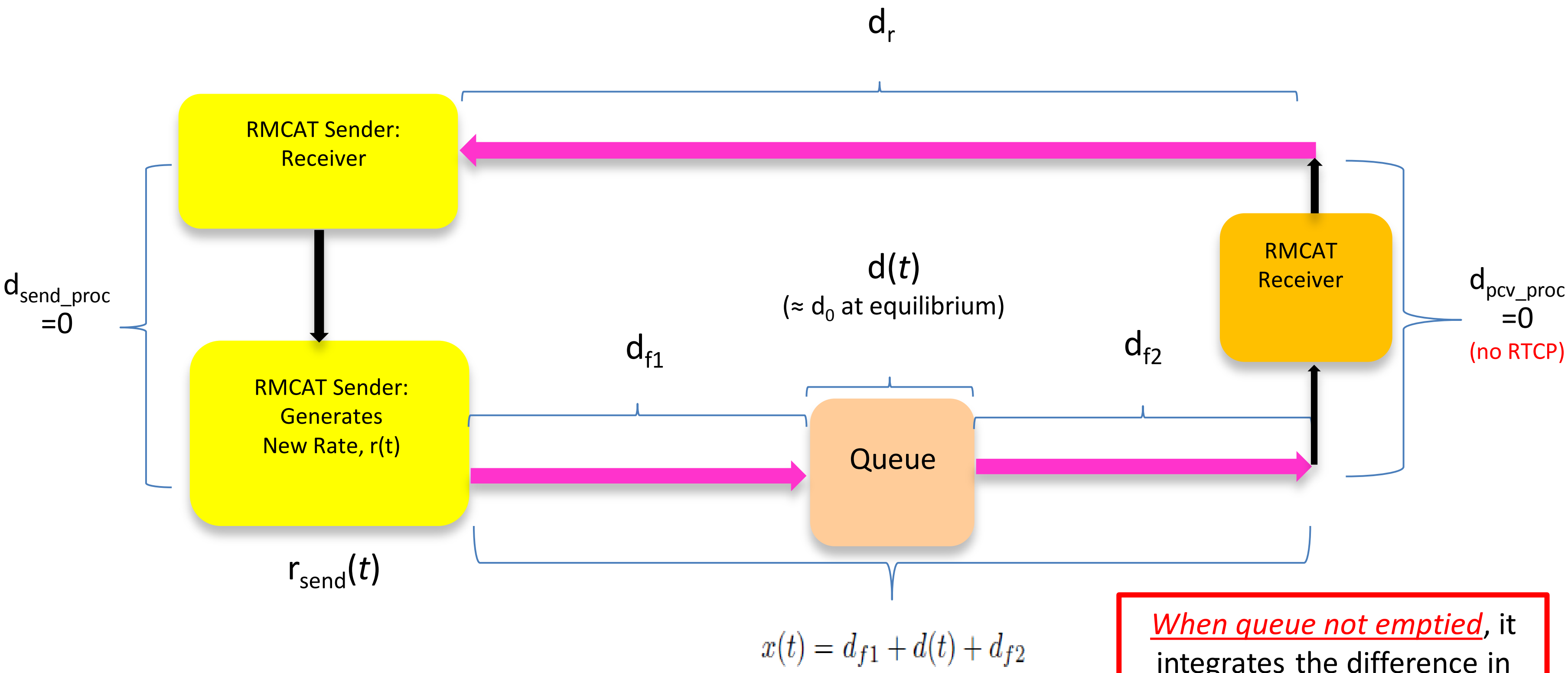
$t_{ack,Z}$ is the earliest time that the queue measurement is available at source (new rate change can occur here).

The time the queue was actually sampled is $t_{queue,Z} = (t_n + d_{f1})$.

The ***effect*** of the rate change on the queue occurs d_{f1} ***after*** the source made the rate change (a full RTT after ***the queue*** was sampled)!

Let's define ***continuous time t*** for fluid-flow modelling of the rate adaption component. That is, let $(t - t_{OFFSET})$ represent times offset from time t.

RMCAT: Continuous Time Modeling for Control Loop



When queue not emptied, it integrates the difference in rates (1/**s** in Laplace Domain).

For small τ;

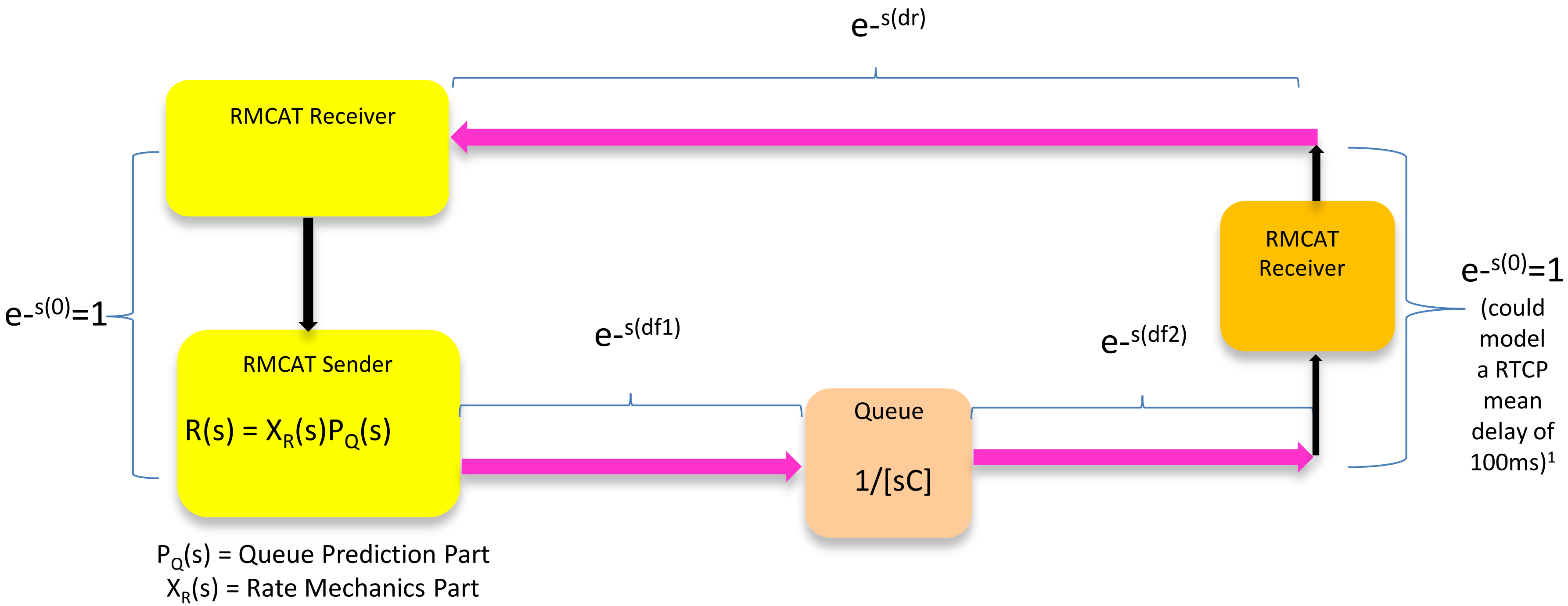
$$q(t) = \max [\, q(t - \tau) + (r_{at\_queue}(t) - C)\tau \,,\, 0 \,]$$

Queue increases/decreases as difference in rates

Also note:

- $r_{at\_queue}(t) = r_{send}(t - d_{f1})$
- $d(t) = q(t)/C$

Control Loop: Laplace Domain (linearize about equilibrium)

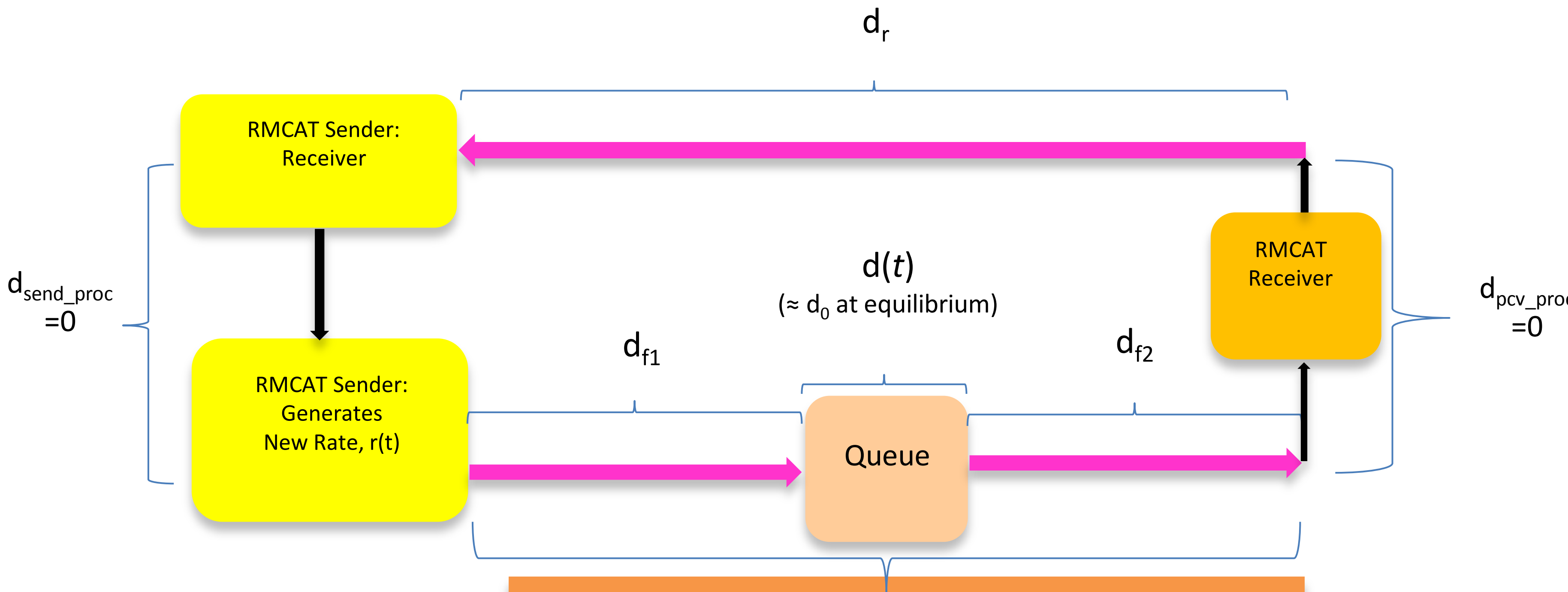


Key Control Loop Observations *At Equilibrium*:

- LTI System => Doesn't matter where prediction or rate control is (sender or receiver).
- Wherever it is, *it WILL take a minimum of a RTT[1] to make a difference at the queue*.

[1] – If the RTCP reporting interval is >> ($d_{f1}+d_{f2}+d_r$), it will dominate. If not, it will look like delay noise to individual delay samples.

So … What is the ***Discrete-Time*** RMCAT RTT Definition?



Forward Delay $= d_{f1} + \{ d(t) |_{t = t_{SAMP}} \} + d_{f2}$

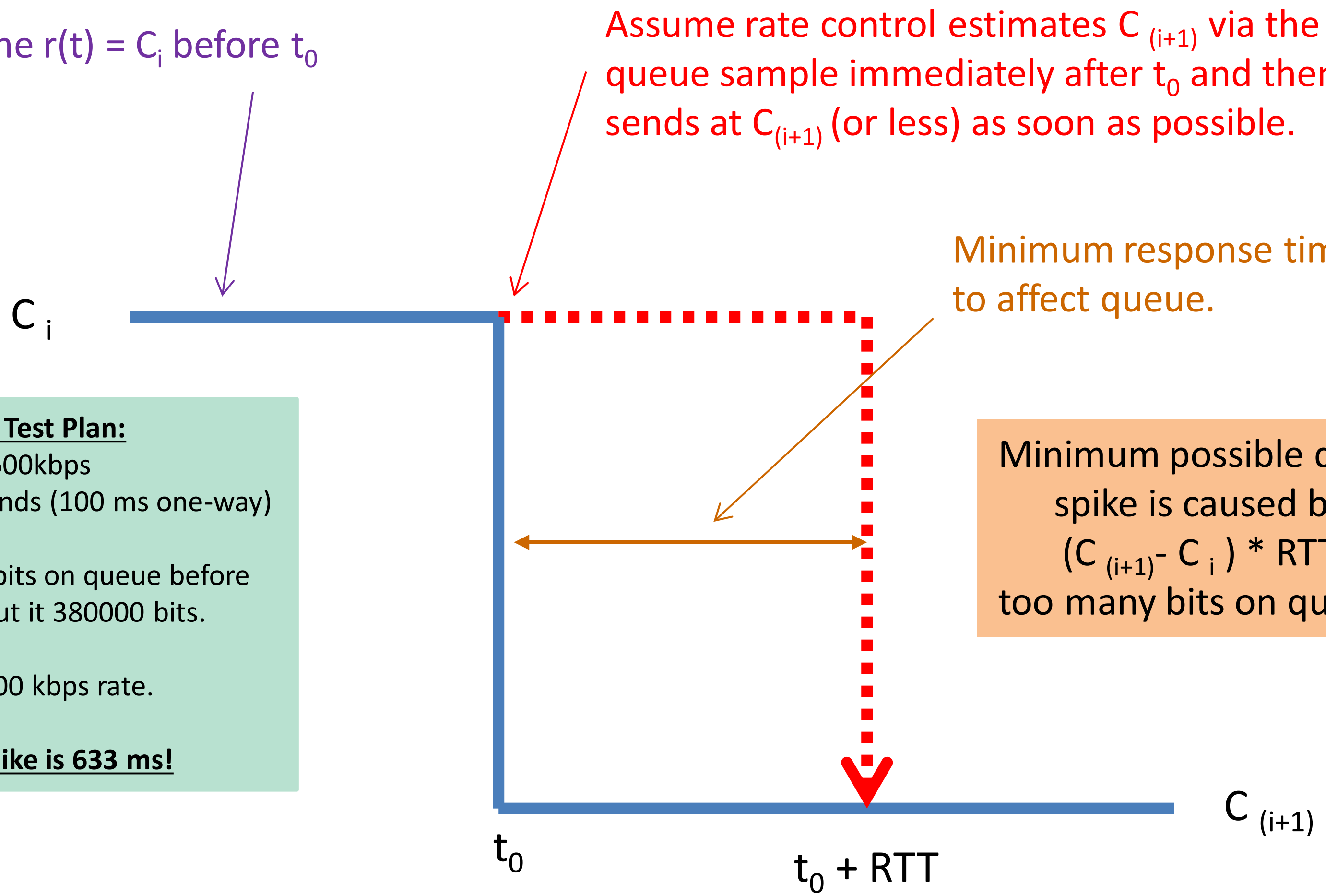
$$\text{RMCAT RTT } (t_i) \; |_{t_i = t_{ACK \text{ for seq Z received}}} = d_{f1} + \{ d(t) |_{t = t_{SAMP \text{ (seq no z)}}} \} + d_{f2} + d_r$$

$$\text{RMCAT RTT } (t_i) \; |_{t_i = t_{ACK \text{ for seq z received}}} = d_{f1} + d_{f2} + d_r + d(t - [d_x + d_{f2} + d_r]) \,,$$

$$\text{where } d_x = d(t) |_{t = t_{SAMP \text{ (seq no z)}}}$$

Queue Delay Variation During Downward Capacity Change

Fastest Possible Rate Adaptation Example (imprudently quick)



<u>Example in IETF RMCAT Test Plan:</u>
Capacity: 2500 kbps -> 600kbps
Assume RTT: 0.200 seconds (100 ms one-way)

Minimum ADDITIONAL bits on queue before we can do anything about it 380000 bits.

Queue must empty at 600 kbps rate.

<u>Thus minimum delay spike is 633 ms!</u>

Minimum possible delay spike is caused by $(C_{(i+1)} - C_i) * RTT$ too many bits on queue.

Note: If we assumed one-way delay of 50 ms, 316 ms is minimum.

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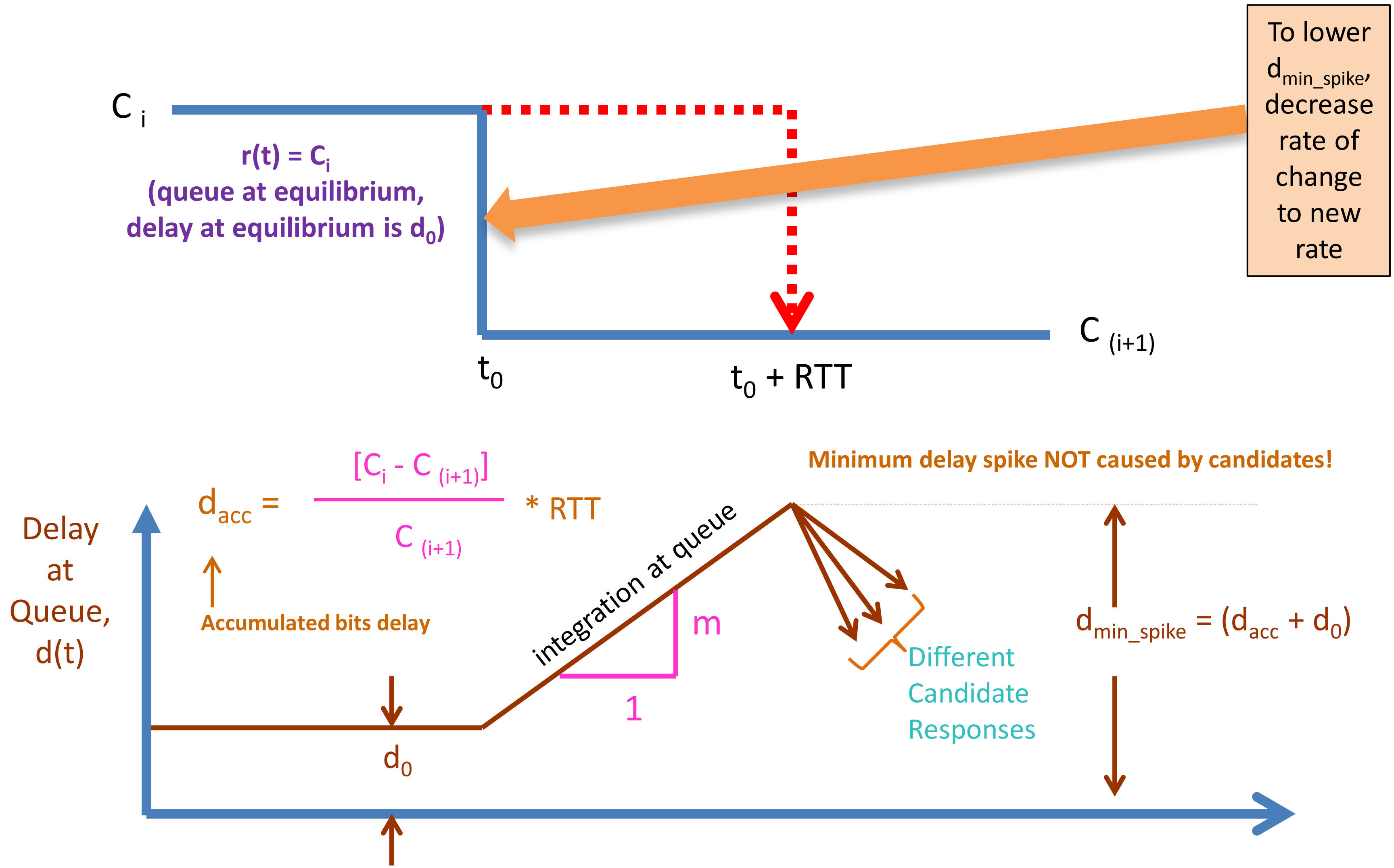

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   - Squelching mechanisms required (self-clocked schemes do this automatically).
   - TCP Dynamics as a function of their RTT.
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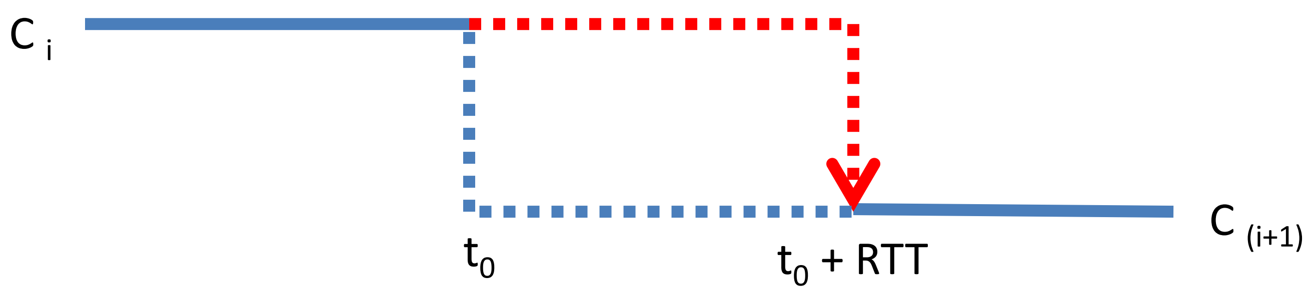
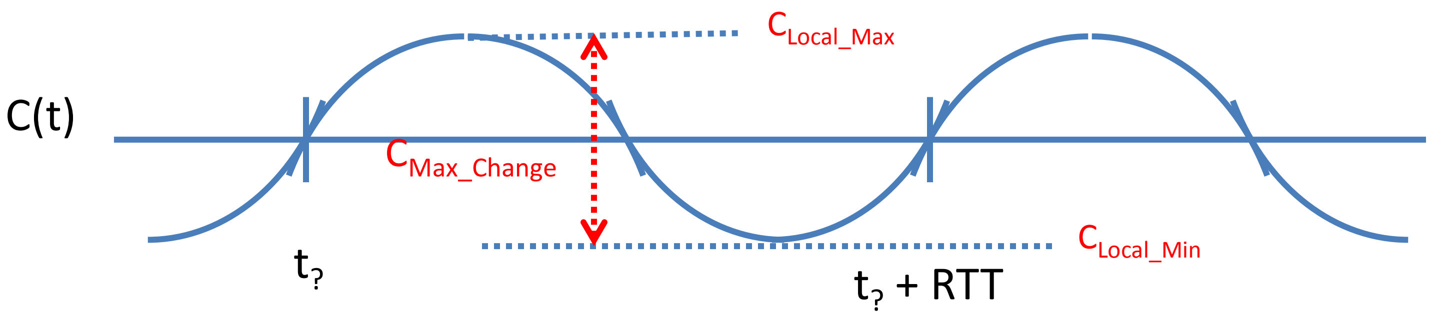
How Quickly Can RMCAT Track Available Capacity Changes? Answer: It Depends on the RTT, Duh!



- The quickest time *__a RMCAT flow__* can possibly “measure” (and “react to”) changes in capacity is bounded by *__ITS__* round-trip time.
- Thus the quickest time it can influence it’s contribution to the queue after a change in capacity is thus bounded by *__ITS__* round-trip time.
- *__Corollary:__* RMCAT flows with different RTTs can react to changes on different time scales (which correspond to their individual RTTs). Just like TCP!
- A reasonable ASSUMPTION for the *__fastest__* time-rate-of-change in available capacity is one which could be tracked (i.e., measured and reacted to) by a RMCAT flow with *__an assumed worst-case RTT__* and *__RTCP interval__*.

A reasonable assumption bound for RMCAT time rate of change in available capacity



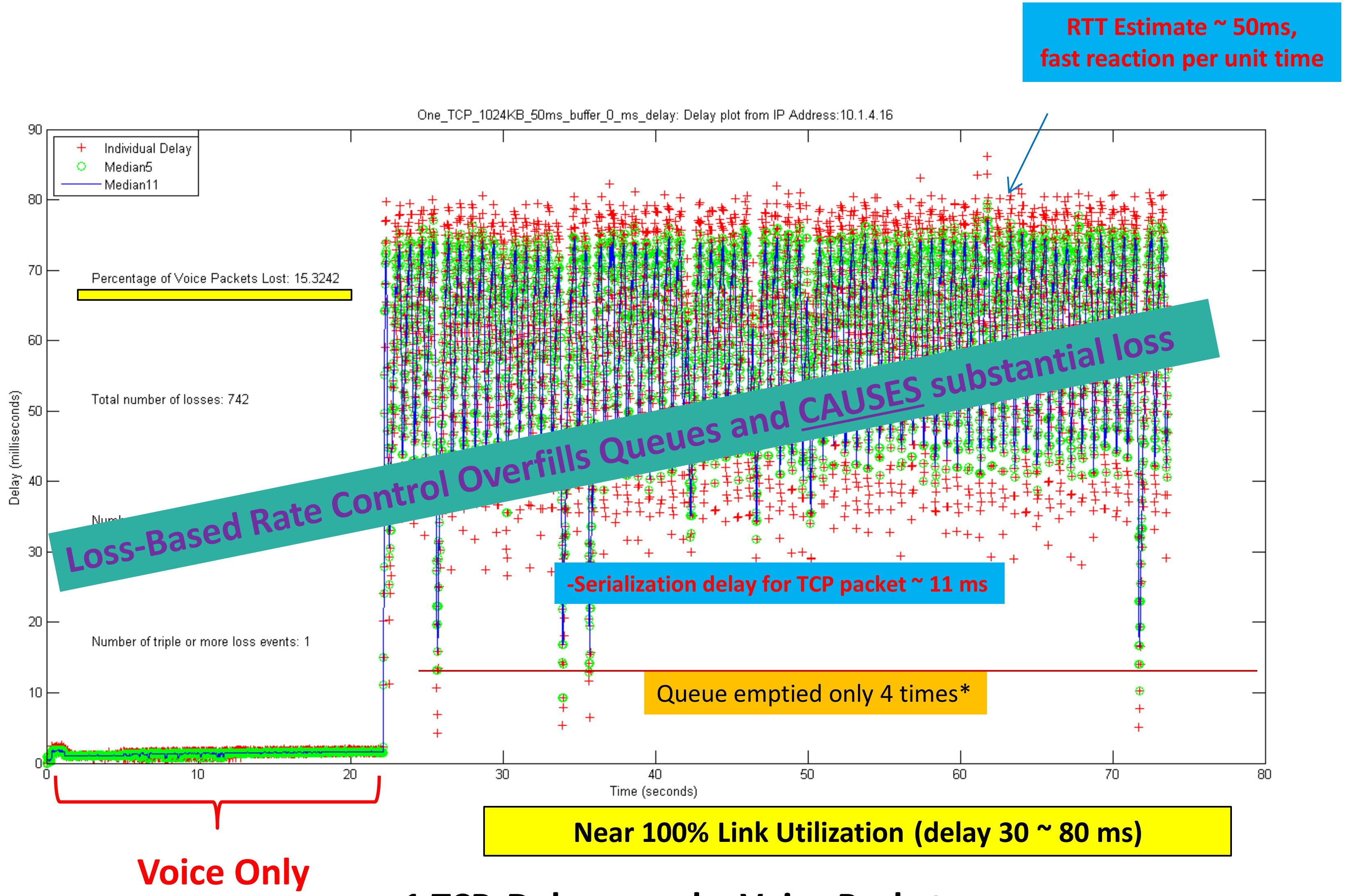
- Assume worst-case RMCAT RTT of ~250 ms (¼ sec).
- Highest capacity change "frequency" that is actionable is $f_{MAX} \approx 4$ Hz.
  - Capacity changes faster than this CANNOT be "seen/sensed/measured" and then "actionable" by a RMCAT flow with the "worst-case RTT".[1]
- Ditto for ACK-based, "self-clocked", protocols like TCP, SCReAM too!
  - TCP can't know to stop within this time either; as they only stop after their ACKs stop.
  - TCP thus "pounds the queue" causing gross overflow events on long RTT connections too!
- Corollary: "Fast Response" is a matter of the ***worst-case capacity change assumption*** - not a fundamental property of "self-clocked" protocols.[2]

1 – If other information was known (e.g., form), predictive components could react quicker.

2 - Rebuttal to: http://conferences.sigcomm.org/sigcomm/2014/doc/slides/150.pdf

TCP Dynamics as a Function of the RTT

1 TCP: Voice Delay, 50 ms BE Queue

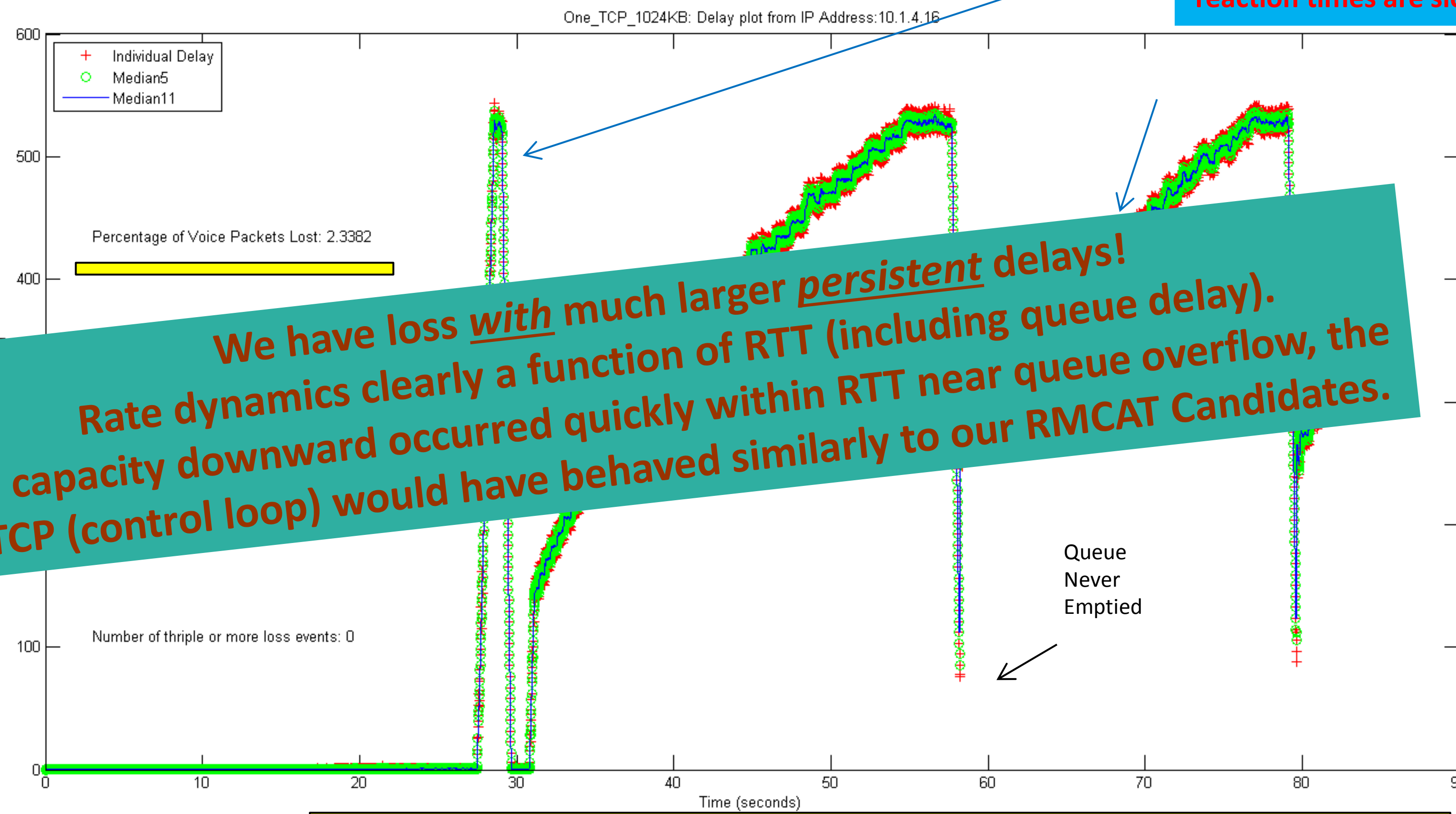


1 TCP, Delay seen by Voice Packets

TCP Dynamics as a Function of the RTT

1 TCP: Voice Delay, 500 ms BE Queue

RTT Estimate now includes queuing delay … subsequent rate increase reaction times are slowed.

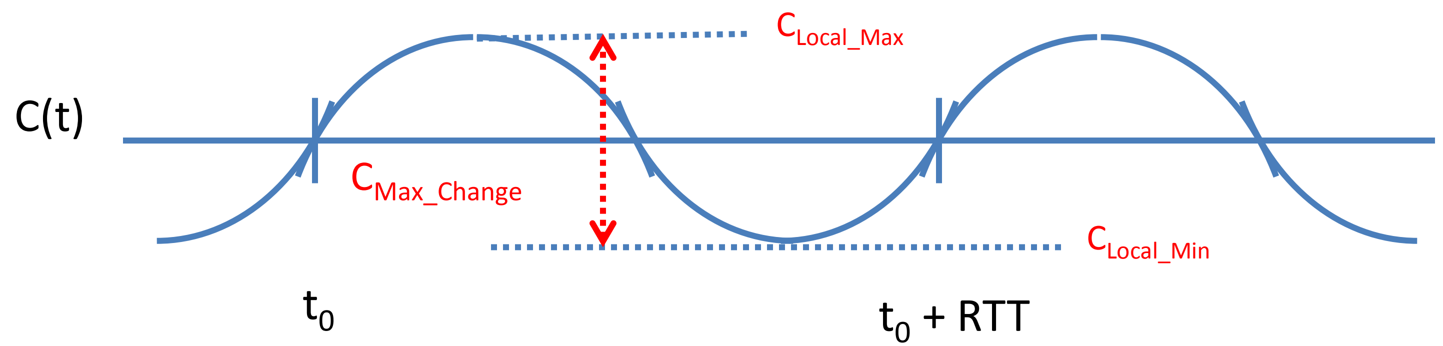


We have loss *with* much larger *persistent* delays!
Rate dynamics clearly a function of RTT (including queue delay).
If capacity downward occurred quickly within RTT near queue overflow, the TCP (control loop) would have behaved similarly to our RMCAT Candidates.

100% Link Utilization (delay 100 ~ 500 ms)

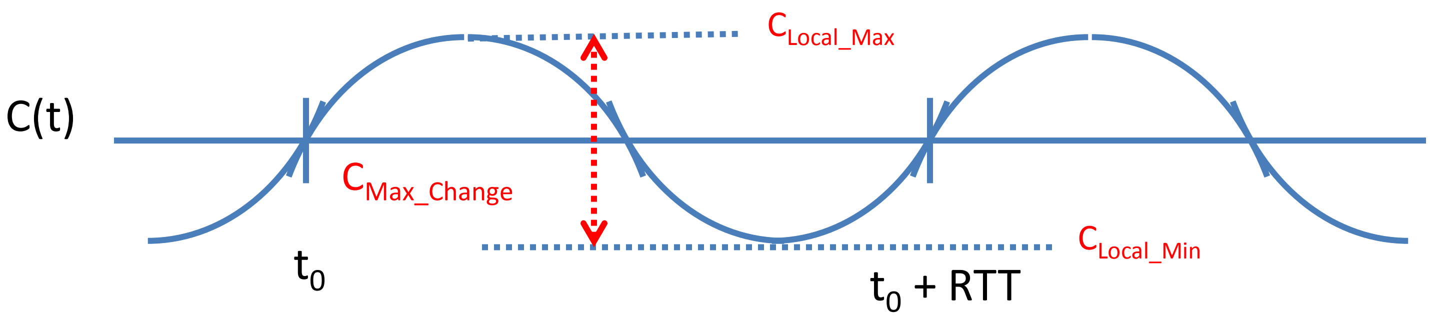
1 TCP, Delay seen by Voice Packets

ACK-Gated RMCAT Proposals (a la Ericsson)



- On long-RTT connections, ACK-gated protocols will also hit the queue too hard and build up excess delay. They will "stop" quickly – but that is a matter of degree (by comparison to how rate-based designs) – not because of some more beneficial property of ACK-gated protocols.*
- Once a worst-case RTT assumption has been made, it imposes a theoretical constraint on how quickly *ANY RMCAT FLOW* can adapt to it.
  - Thus imposing a "hidden assumption" on the time-rate-of-change of capacity ANY RMCAT DESIGN on *the worst-case RTT can adapt to*.
- This, in turn, imposes a minimum RTCP spacing constraint:
  - For 250 ms RTT, < π/2 spacing (@4 Hz) implies $T_{RTCP} \leq \sim 62.5$ ms.

Implications for WiFi/LTE/Wireless Adaptation



Repeated/paraphrased from last slide:

On long-RTT connections, ACK-gated protocols will also hit the queue too hard and build up excess delay. They will "stop" quickly – but that is a matter of degree (by comparison to rate-based approaches) – not because of some more beneficial property of "self-clocked" protocols over rate-controlled protocols.

Summary:

- We will need to develop better "squelching conditions" in future enhancements to our present RMCAT designs (i.e., when feedback stops and/or becomes irregular).
- *Complete squelch* is only prudent when there is *no impairment in feedback path*.
- Wireless challenges now become *a known second-order problem*; unless we want to limit RTT (not possible) or go to per-packet feedback (non RTCP approaches).

Summary

1. **RMCAT Discrete Time RTT Formalized**
   - Fluid-flow (continuous-time) model and rigorous RMCAT RTT definition.
2. **How Quick Can ANY RMCAT Design Can Track Capacity Changes**
   - Result is independent of algorithm type ("self-clocked" or "rate-based").
3. **Reasonable Assumptions on Time-Rate-of-Change of Capacity**
   - Worse-case RTT defines "tracking responsiveness" (w/o predictive component).
   - Like TCP, dynamics of RMCAT solution will be a function of their RTT.
   - The feedback intervals and flow RTT will determine capacity tracking ability.
   - Bounding feedback intervals and worst-case RTT effectively bounds best-case tracking.
4. **Implications for Adaptation with Wireless (WiFi/LTE/etc).**
   - Squelching mechanisms required (self-clocked schemes do this automatically).