Three Papers on Congestion Control

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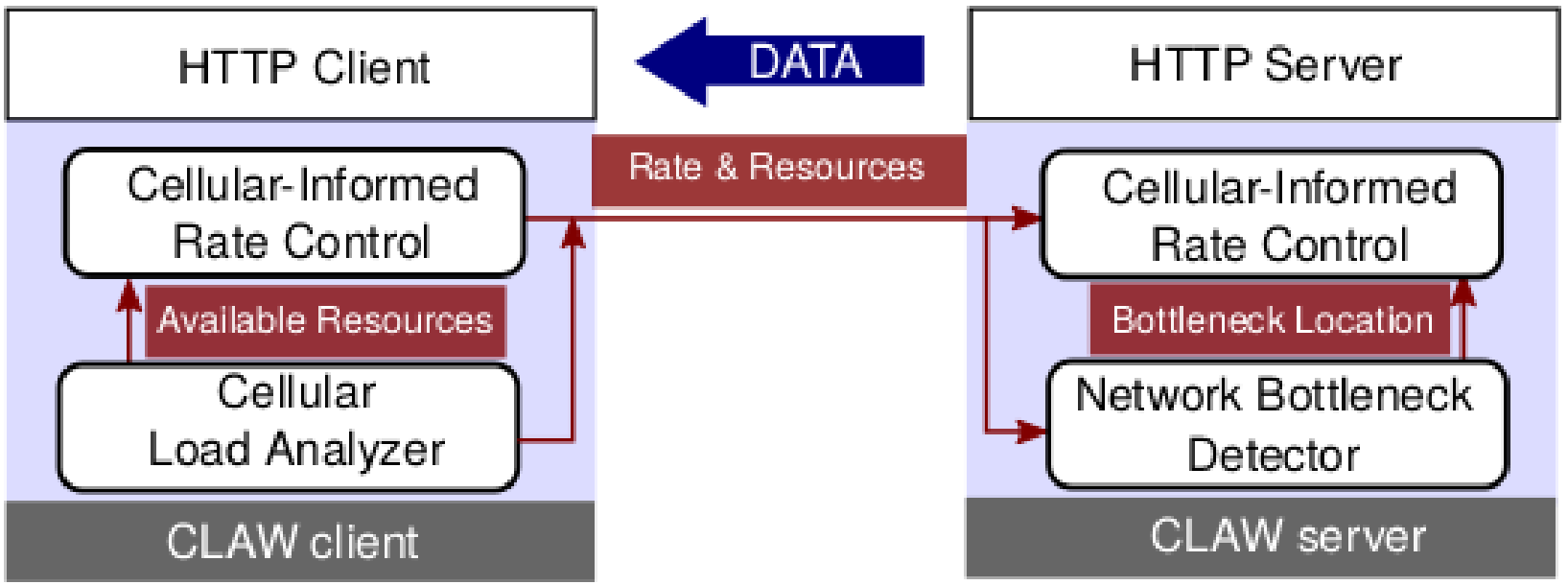
Overview

1. CLAW
2. Sprout
3. PropRate

Accelerating Mobile Web Loading Using Cellular Link Information (CLAW)



Challenge for Web over LTE

- RTTs in LTE fluctuate a lot. A temporary RTT surge may mislead TCP congestion control to regard it as a loss. We need least number of round trip probes to converge to the network bandwidth.
- TCP's multiplicative decrease overreacts to LTE link losses.
- Short mobile web loading flows cannot let TCP quickly converge to network bandwidth. Bandwidth estimation should not be related to source bit rate.
- Obtaining cellular load directly requires full knowledge of LTE BS's resource allocation, which is difficult in commodity mobile devices.

Idea

CLAW's design includes:

- cellular link analyzer that computes available resources allocated to a single client.
- cellular informed rate control to find the optimum bandwidth.
- network bottleneck detector to address the minor case that wireline is the bottleneck

Cellular Link Analyzer

Goal: calculate the cell load: the volume of allocated radio resources on the downlink channel.
Given information: RSSI, RSRP, RSRQ, MCS Fraction of allocated RBs in the $k-th$ subframe is:

$$r_k = A_k / N_{rb} = \frac{Q_k^{-1} - N_{ref}}{(N_{subc}^{rb} - N_{ref}) N_{ant}}$$

Then, within a sliding window T, we can compute the number of RBs allocated to all clients as well as the number of idle RBs.

$$N_I = N_t - N_a = 2TN_{rb}(1 - L)$$

S_k, The number of RBs allocated to the client itself, can be read from the phone's dignostic interface. Sum them up and we obtain

$$N_s = \sum_{k=1}^{T} S_k$$

And the number of available RBs in this window T is $N_f = N_I + N_s$

Cellular-Informed Rate Control

Use $F(\cdot)$ to map MCS and number of RBs per subframe (N_f / T_i) to transport block size (number of bytes that can be carried over a subframe). Further multiply it by T_i to obtain the potential capacity

$$\hat{B} = T_i F(N_f / T_i, \overline{MCS})$$

Ideally, $\hat{B}$ is the BDP. Client sends this to the server and server decides W_{claw}. This causes only one RTT.
New flows will use the maximum of cwnd calculated by cubic and claw to ensure fairness.
RLC-layer statistics are used to distinguish link loss from congestion.

Network Bottleneck Detector

CLAW compares the volumes of resources N_f available to a client and its consequently allocated amount of resources U after one RTT,

- If $U < \delta N_f$, detector declares a wireline bottleneck. Falls back to TCP-style control
- Bottleneck is asserted only after consistent observation over a sliding window of 3 RTTs.
- δ is set to 0.8 empirically.

Implementation

For client side,

- Android phones with Qualcomm chipsets are used.
- Read output logs by Qualcomm's QCAT.
- Modify `tcp_output.c` to set extra bit of confirming rate control algorithms

For server side,

- Test website is an Apache HTTP/2 server, which also acts as a CLAW sender.
- Upon receiving the estimated cwnd size by client, pass it to the rate control algorithm.
- Records packet losses, retransmissions, ACKs and behaviors of CLAW in real time.

Evaluation Setup

- Benchmark against CQIC and Verus.
- CQIC is upgraded from original HSPA+ to LTE and Verus is implemented in the Linux kernel.
- Websites are on the list of Alexa top sites. Elements may include dynamic JS ones.
- PLT is measured using Chrome Developer Tools.
- Phones run chrome browser with cache option disabled.
- Configure phones to LTE only.

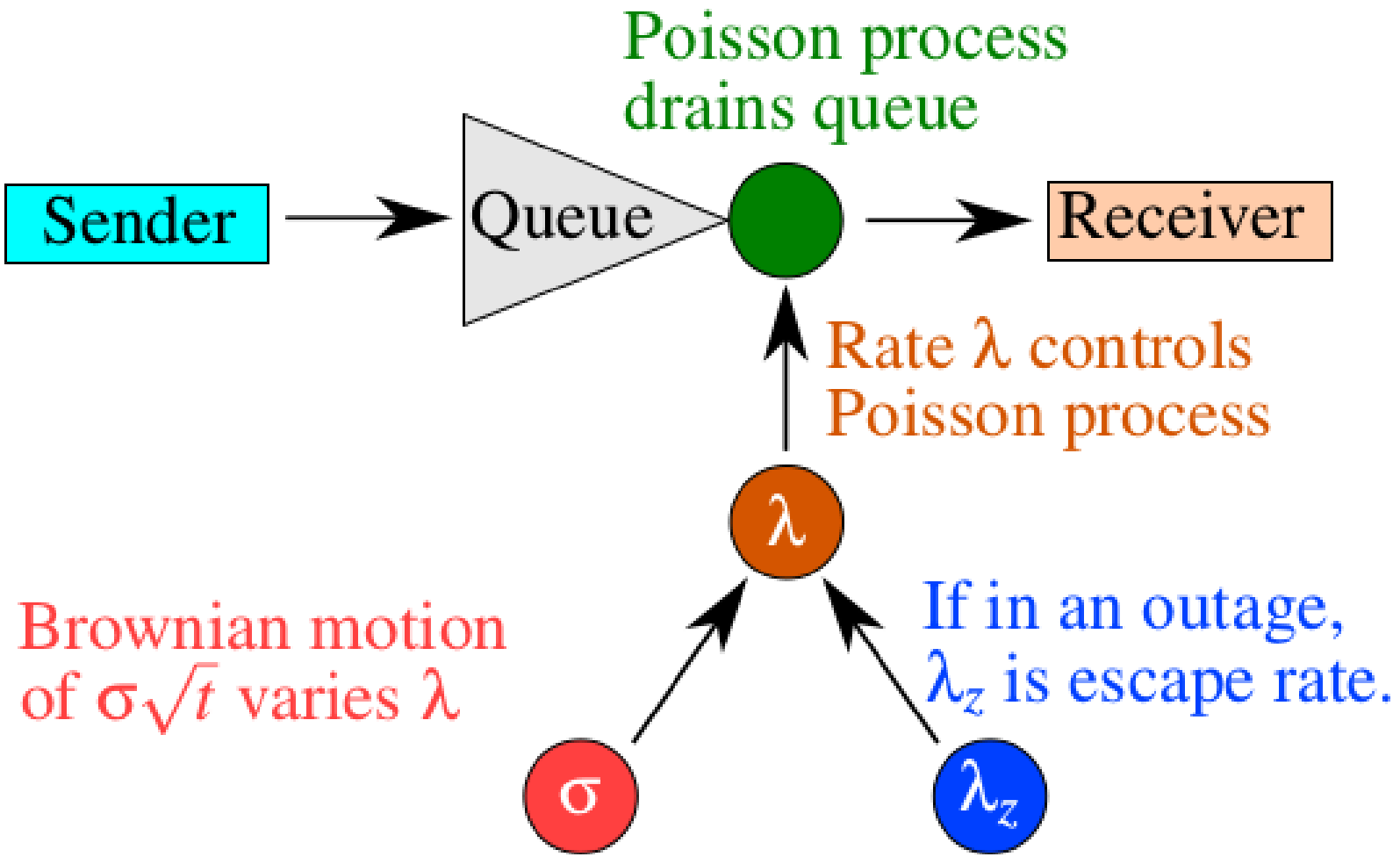
Micro-benchmarks

- Cellular load anaylzer: Generate `iperf` TCP traffic stream with linearly increasing bitrate. Smoothed cell load follows the traffic rate measured by `tcpdump`.
- Cellular-informed rate control: Load the same webpage using both CLAW and CUBIC and observe the cwnd size and LTE resource utilization.
- Bottleneck detector: Manually throttle the web server's network interface at 30kbps using `Dummynet` kernel module. Without the detector, CLAW's performance becomes comparable to CUBIC. With it, CLAW outperforms CUBIC by 20%.

System Level Test

- Load 20 selected pages from top 200 Alexa list and compare PLT with CUBIC and other transport protocols.
- Under different cell loads: run at different time of the day.
- Under different LTE channel qualities.
- Under different outdoor mobility scenerios.
- Over different cellular operators.
- Over different LTE hardware: Nexus 5 and Nexus 5X
- With HTTP/1.1 and HTTP/2
- TCP friendliness: Evaluate PLT on different combinations of two protocols.

Stochastic Forecasts Achieve High Throughput and Low Delay over Cellular Networks (Sprout)



Motivation, Context and Challenges

- Cellular wireless network is not stable. Bandwidth varies rapidly and outages occurs occasionally.
- Base stations schedules isolates queues of different users.
- Traditional methods may either over-buffer the queue or under-utilize the link.

The challenges for a good transport protocol:

- Link rate variations.
- Over-buffering results in high delay while under-utilization leads to low quality.
- Outages should be dealt with.

Basic Idea of Sprout

The interarrival packets follows a Poisson process. If the rate λ can be estimated using a certain model, it may help when infering how many bytes the link will be willing to transmit from its queue in near future.
Idea:

- λ itself varies in a Brownian motion. This property can be used to get a more precise value of λ.
- We can conduct an inference update procedure every 20ms (a tick) to determine the most appropriate value of λ in 256 discrete values sampled uniformly from 0 to 1000 MTU-sized packets per second.

Evolution of the probability distribution on λ

At every tick, Sprout conducts the following steps:

- Evolves probability distribution based on Brownian motion to each $\lambda \neq 0$. For $\lambda = 0$, use outage escape rate.
- Observes the number of bytes that actually came in during the most recent tick. Update the estimates of probability:

$$F(x) \leftarrow P_{old}(\lambda = x)\frac{(xT)^k}{k!}e^{(-xT)}$$

- Normalize the probability by the estimation:

$$P_{new}(\lambda = x) \leftarrow \frac{F(x)}{\sum_{i=1} F(i)}$$

Forecasting

- Sprout calculates a packet delivery forecast with a cautious estimate with error less than 5%. It sums over each λ to find the probability distribution of the cumulative number of packets that will have been drained by that point of time.
- Receiver will deliver this estimation to the sender. To help with the estimation, sender will provide required information (See sec3.4 in paper).
- Sender uses the most recent forecast to calculate a window size. It looks ahead five ticks and use the expected number of drained packets subtract the current queue occupancy estimate to obtain the "safe-to-send" bytes estimation.

Experimental Testbed

Goal: use trace-driven emulation to capture the variability of cellular network.

- Saturator: Use a laptop connected two phones, with one phone's link saturated and another phone returning feedbacks. Different types of android phones are used.
- Cellsim: Input saturated traces to an emulator. This link has a one-way delay for about 20ms (40ms RTT).
- SproutTunnel: Established over a UDP channel to carry arbitrary traffic across a cellular link. Seperates each flow into its own queue.

Evaluation

Compared against TCP Vegas, LEDBAT, and Cubic. Evaluates Sprout and Sprout-EWMA. Metrices:

- Throughput: total number of bits received by an application divided by duration of the experiment.
- self-inflicted delay: lower bound of end-to-end delay between sender and receiver (since sending the most recent packet)

TCP Congestion Control Beyond Bandwidth-Delay Product for Mobile Cellular Networks (PropRate)

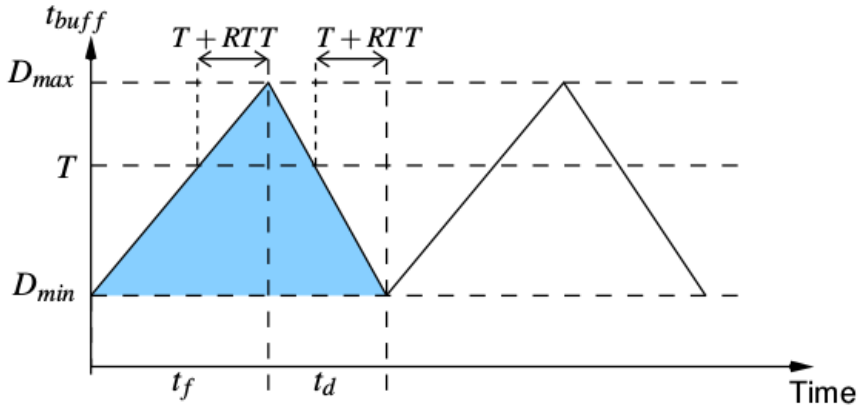


Figure 1: Buffer full (throughout optimal) case: buffer delay oscillates between D_{max} and D_{min}.

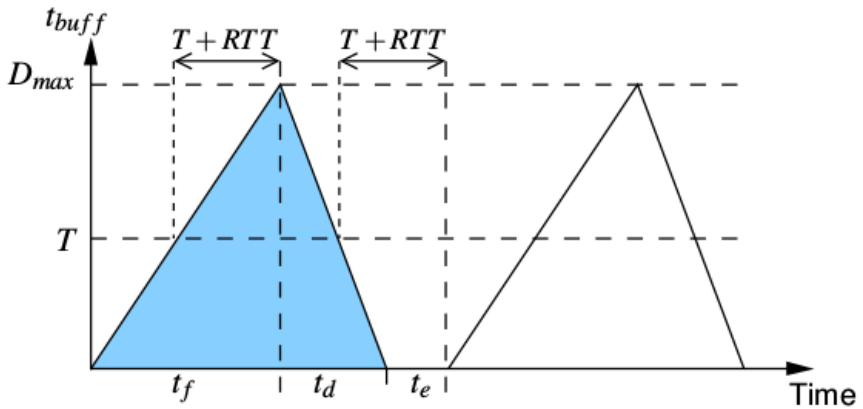


Figure 2: Buffer emptied (delay sensitive) case: buffer delay oscillates between D_{max} and 0.

Motivation

- Current cwnd-based congestion control mechanism intimately couples congestion control and packet dispatch, which provides TCP with only indirect control of effective data rate.
- Saturation of cwnd-based mechanism works well only for small buffers.
- Automatic retransmission mechanism and fair scheduling at LTE BSes are two important cellular network features.
- Idea: Directly regulate packets in the bottleneck buffer.

Features of PropRate

- Uses the buffer delay as the congestion signal, and performs rate control by having the sending rate oscillate around the estimated receive rate.
- Allows an application to set desired maximum latency.
- Uses one-way delay to do the estimation.
- Divided into two phases, buffer fill and buffer drain.

Variable Name	Meaning	Dependent on
$\bar{t}_{buff}$	User specified buffer delay	None
t_{buff}	Instantaneous buffer delay	Measurement
T	Threshold of switching states	$\bar{t}_{buff}$
k_f, k_d	Proportion to set sending rate	$\bar{t}_{buff}$
$\mathbb{U}$	Bottleneck-buffer utilization	T, k_f, k_d
D_{max}, D_{min}	Max/Min instant buffer delay	T, k_f, k_d

Big Picture

- User specifies the buffer delay $\bar{t_{buff}}$ and the algorithm tries to keep the periodic delay in $\bar{t_{buff}}$.
- Assume the estimated bottleneck bandwidth is ρ.
- When the instantaneous buffer delay t_{buff} is lower then threshold T, enter buffer fill state; otherwise enter buffer drain state.
- Buffer fill state sends a bit faster than ρ, and buffer drain state sends slower.
- Sending rate is adjusted to $\sigma_f = k_f \rho, \sigma_d = k_d \rho$.
- Utilization of the bandwidth is the time proportion when buffer is not empty.

$$U = \frac{t_f + t_d}{t_f + t_d + t_e}$$

Big Picture (Contd)

- It can be further calculated that

$$\bar{t_{buff}} = \begin{cases} \frac{D_{max}+D_{min}}{2} & \text{, buffer full case} \\ \frac{D_{max}}{2} U & \text{, buffer empty case} \end{cases}$$

- D_{max} and D_{min} can be determined by the buffer delay threshold T.
- k_f and k_d are slope of the $t_{buff} - time$ diagram.
- State change is delayed by one RTT. Thus the overhead is $T + RTT$

Optimization

Optimization for throughput (setting T and D_{min}):

- To minimize state change time (preventing the diagram from being skewed), set $T = \bar{t_{buff}}$.
- Set $D_{min} = \bar{t_{buff}}/2$ to fully utilize the link.

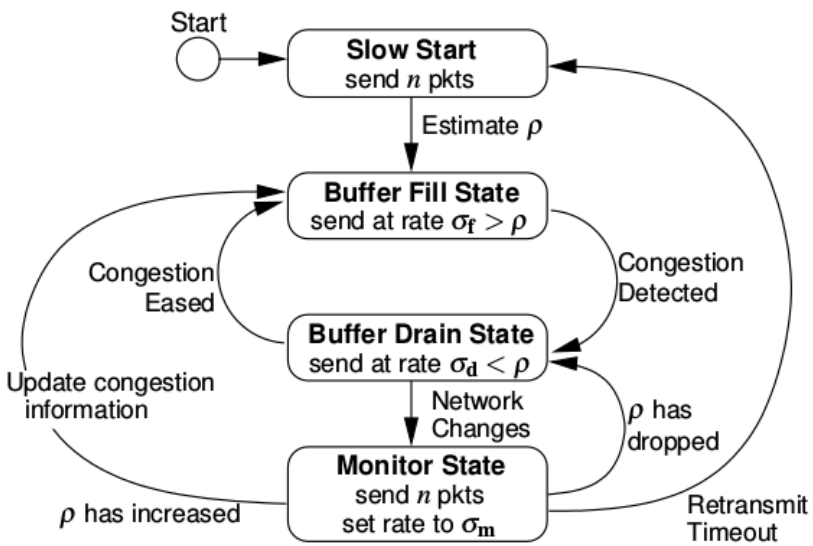
Optimization for latency (setting D_{max}):

- Transmission delay and queuing delay are considered.
- If an application specified the maximum allowed delay L_{max}, we should have $RTT + D_{max} \leq L_{max}$
- By experiment, let $D_{max} = U^3(L_{max} - RTT)$, where RTT is round trip time excluding buffer delay.

Then, $t_{buff} \leq L_{max} - RTT$, we can set all mentioned parameters accordingly. The threshold T can be adjusted with an exponentially weighted moving average empirically.

State Transition

- Slow start: send 10 packets to obtain ρ.
- Buffer fill and buffer drain state after slow start. Retransmission timeout returns to slow start state.
- If staying in buffer drain state for too long, go to monitor state to obtain the current receiving rate and check background link condition.



(b) Rate-based mechanism.

Implementation

Buffer regulation:

- Limit the number of packet allowed to be transmitted to $RTT * \rho$ before entering monitoring mode.
- t_{buff} is estimated by the difference of current observed one-way and the minimum one-way delay observed in the recent past.

Bandwidth estimation and rate control:

- Bandwidth is estimated at sender when TCP timestamp option is on.
- Server sends `TSval` back to the sender. Sender can estimate the bandwidth according to ACK number and difference between two `TSval` values.

Evaluation Testbed

- Cellsim is used to generate network traces.
- Collect two sets of traces: stationary and mobile. 3 ISPs are tested for each set.
- `tcpdump` is used to capture packet traces.
- Use `iperf` to generate traffics.
- Target average buffer delay t_{buff} is set to 20ms, 40ms, and 80ms.

Metrics and Results

- Compared against many different algorithms (10 algorithms).
- The throughput and latency trade-off is good in all 6 traces. However, PropRate does not respond well to network outage.
- Effectiveness of negative feedback loop (updating T): test with and without NFL.
- Uses practical LTE network to validate the effectiveness of Cellsim's emulation result.
- Tests contention against itself and CUBIC to validate TCP-friendliness.
- Tests computational overhead by measuring CPU utilization ratio.