Stochastic Forecasts Achieve High Throughput and Low Delay over Cellular Networks

Keith Winstein, Anirudh Sivaraman, and Hari Balakrishnan

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April 5, 2013
Cellular networks are variable

Verizon LTE uplink throughput

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Cellular networks are too reliable

(Verizon LTE, one TCP download.)
Interactive apps work **poorly**

- We measured cellular networks while driving:
  - **Verizon LTE**
  - Verizon 3G (1xEV-DO)
  - AT&T LTE
  - T-Mobile 3G (UMTS)
- Then ran apps across replayed network trace:
  - **Skype** (Windows 7)
  - Google Hangout (Chrome on Windows 7)
  - Apple Facetime (OS X)
Performance summary

Verizon LTE Downlink

Throughput (kbps)

Self-inflicted delay (ms)

Better

Skype

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Why is performance so bad?

- Exiting schemes react to congestion signals.
  - Packet loss.
  - Increase in round-trip time.
- Feedback comes too late.
- The killer: self-inflicted queueing delay.
- Throughput overshoot means a queue filling up.
Sprout’s goal

- Most throughput
- Bounded risk of delay $> 100$ ms
Bounded risk of delay

- **Infer** link speed from interarrival distribution.
- **Predict** future link speed.
  - Don’t wait for congestion.
- **Control**: Send as much as possible, but require:
  - 95% chance all packets arrive within 100 ms.
Infer: link speed from flicker noise process

(Verizon LTE, phone stationary.)
Predict: future link speed

- Model evolution of speed as **random walk**.
  - (Brownian motion)
- Cautious forecast: 5th percentile cumulative packets
- Receiver makes forecast; sends back to sender in ack
- Almost all precalculated
Sprout’s model

- Poisson process drains queue
- Rate $\lambda$ controls Poisson process
- Brownian motion of $\sigma \sqrt{t}$ varies $\lambda$
- If in an outage, $\lambda_z$ is escape rate.
### Parameters

Volatility $\sigma$: fixed @ $200 \frac{\text{pkts/s}}{\sqrt{s}}$

Expected outage time $1/\lambda_z$: 1 s

Tick length: 20 ms

Forecast length: 160 ms

Delay target: 100 ms

Risk tolerance: 5%

All source code was **frozen before data collection began**.
Control: fill up 100 ms forecast window

Cumulative packets sent vs. time (ms) for a cautious forecast.
**Control**: fill up 100 ms forecast window

Cumulative packets sent vs. time (ms) graph showing a cautious forecast.
**Control:** fill up 100 ms forecast window

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Control: fill up 100 ms forecast window
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**Control**: fill up 100 ms forecast window

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Throughput (kbps) vs. Self-inflicted delay (ms) for Verizon LTE Downlink.

Verizon LTE Downlink

Better

Skype

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Verizon LTE Downlink

Throughput (kbps) vs. Self-inflicted delay (ms)

- Better
- LEDBAT
- Vegas
- Compound TCP
- Facetime
- Skype
- Google Hangout

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Throughput (kbps)

Self-inflicted delay (ms)

Verizon LTE Downlink

Sprout-EWMA

Sprout

LEDBAT

Vegas

Compound TCP

Cubic

Facetime

Skype

Google Hangout

Better
Stochastic Forecasts Achieve High Throughput and Low Delay over Cellular Networks
Verizon 3G (1xEV-DO) Downlink

Throughput (kbps) vs. Self-inflicted delay (ms)

- Cubic
- Compound TCP
- Sprout-EWMA
- LEDBAT
- Vegas
- Sprout
- Google Hangout
- Facetime
- Skype
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AT&T LTE Downlink

Self-inflicted delay (ms)

Throughput (kbps)

Sprout-EWMA

Sprout

Cubic

Facetime

Compound TCP

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Vegas

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Throughput (kbps) vs. Self-inflicted delay (ms) for AT&T LTE Uplink.

- **Cubic**
- **LEDBAT**
- **Compound TCP**
- **Sprout-EWMA**
- **Vegas**
- **Skype**
- **Facetime**
- **Google Hangout**

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Stochastic Forecasts Achieve High Throughput and Low Delay over Cellular Networks
T-Mobile 3G (UMTS) Downlink

Throughput (kbps) vs. Self-inflicted delay (ms)

- Sprout-EWMA
- LEDBAT
- Vegas
- Sprout
- Compound TCP
- Skype
- Google Hangout
- Facetime
- Cubic

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T-Mobile 3G (UMTS) Uplink

Throughput (kbps)

Self-inflicted delay (ms)

Cubic

LEDBAT

Sprout-EWMA

Vegas

Compound TCP

Facetime

Skype

Google Hangout

Sprout

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## Overall results

<table>
<thead>
<tr>
<th>Sprout vs.</th>
<th>Avg. speedup</th>
<th>Delay reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skype</td>
<td>2.2×</td>
<td>7.9×</td>
</tr>
<tr>
<td>Hangout</td>
<td>4.4×</td>
<td>7.2×</td>
</tr>
<tr>
<td>Facetime</td>
<td>1.9×</td>
<td>8.7×</td>
</tr>
<tr>
<td>Compound</td>
<td>1.3×</td>
<td>4.8×</td>
</tr>
<tr>
<td>TCP Vegas</td>
<td>1.1×</td>
<td>2.1×</td>
</tr>
<tr>
<td>LEDBAT</td>
<td>Same</td>
<td>2.8×</td>
</tr>
<tr>
<td>Cubic</td>
<td>0.91×</td>
<td>79×</td>
</tr>
</tbody>
</table>
Varying risk tolerance

Throughput (kbps) vs. Self-inflicted delay (ms)

- Cubic
- LEDBAT
- Compound TCP
- Vegas
- Sprout (5%)
- Skype
- Facetime
- Google Hangout

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Competes with AQM even though end-to-end

![Graph showing utilization (percent) vs. self-inflicted delay (ms) for Cubic, Cubic-over-CoDel, Sprout, and Sprout-EWMA.]
Competing traffic **inside** Sprout tunnel

<table>
<thead>
<tr>
<th></th>
<th>Direct</th>
<th>via Sprout</th>
<th>Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cubic throughput</td>
<td>8336 kbps</td>
<td>3776 kbps</td>
<td>$0.5 \times$ (= worse)</td>
</tr>
<tr>
<td>Skype throughput</td>
<td>78 kbps</td>
<td>490 kbps</td>
<td>$6 \times$</td>
</tr>
<tr>
<td>Skype 95% delay</td>
<td>6.0 s</td>
<td>0.17 s</td>
<td>$35 \times$</td>
</tr>
</tbody>
</table>

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Replication by Stanford students (February–March 2013)

- Alterman & Quach reproduced some of our measurements
  - http://ReproducingNetworkResearch.wordpress.com/2013/03/12/1216/
- Won best project award in Stanford networking class!
M.I.T. 6.829 contest (March–April 2013)

- Turnkey network emulator, evaluation
- Sender, receiver run in Linux containers
- 4th prize: $20
- 3rd prize: $30
- 2nd prize: $40
- (If beat Sprout) 1st prize:
M.I.T. 6.829 contest (March–April 2013)

- Turnkey network emulator, evaluation
- Sender, receiver run in Linux containers
- 4th prize: $20
- 3rd prize: $30
- 2nd prize: $40
- (If beat Sprout) 1st prize: Co-authorship on future paper
Baseline

Throughput (Mbps)

Delay (ms @ 95th percentile)

Omniscient

Sprout

Skype

Better
Land of 3,000 student protocols

Stochastic Forecasts Achieve High Throughput and Low Delay over Cellular Networks
Sprout is on the frontier

Throughput (Mbps) vs. Delay (ms @ 95th percentile)

Sprout and Omniscient compared to Skype.
Limitations

- Only evaluated long-running flows.
- All testing data from Boston.
- User should wrap competing flows inside Sprout.
- If queue is full of another user’s packets, an end-to-end scheme can’t help.
  - Fortunately, cells have per-device queues...
  - ...but Wi-Fi generally doesn’t.
- What about when the cell link isn’t the bottleneck?
Our approach

- Pick a model, any model.
- All models are wrong, but they help anyway!
- See if it lands on the frontier.*
  * (On a large set of real network paths or newly-collected traces.)
- Kaizen for congestion
Thank you

- Lakshminarayanan Subramanian
- Shuo Deng
- Jonathan Perry
- Katrina LaCurts
- Andrew McGregor
- Tim Shepard
- Dave Täht
- Michael Welzl
- Hannes Tschofenig
- Wireless@MIT members (http://wireless.csail.mit.edu)
- NSF & Shannon family (fellowship)
Sprout for controlled delay over cellular networks

- **Infer** link speed from interarrival distribution
- **Predict** future link speed
- **Control** risk of large delay with cautious forecast
- Yields $2–4\times$ throughput of Skype, Facetime, Hangout
- Achieves $7–9\times$ reduction in self-inflicted delay
- Matches active queue management **without router changes**
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