Transport Architectures for an Evolving Internet

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CSAIL

Joint work with Anirudh Sivaraman, Pratiksha Thaker, and Hari Balakrishnan.

The Internet evolves

In 20 years, computer networks have seen dramatic change:

- Wi-Fi
- Cellular networks
- Datacenters
- 10 GigE
- Transoceanic links

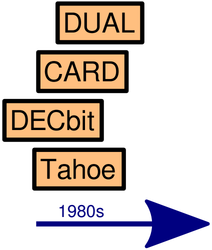
- Ubiquitous mobility
- Huge amounts of streaming video

Coping with change

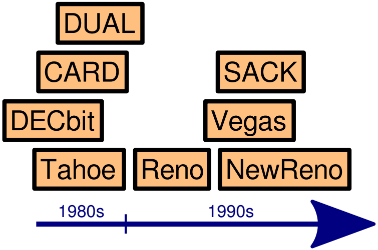
How should users deal with an evolving network?

One approach: design new protocols.

The march of congestion-control protocols



The march of congestion-control protocols



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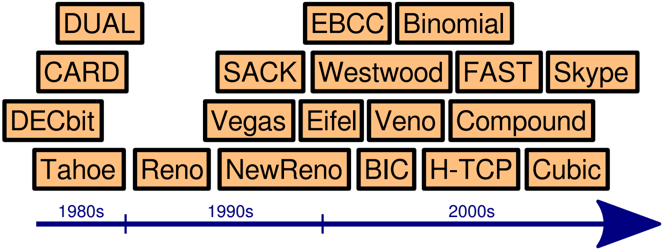

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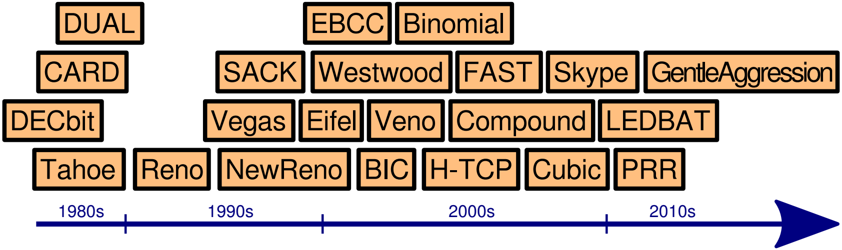

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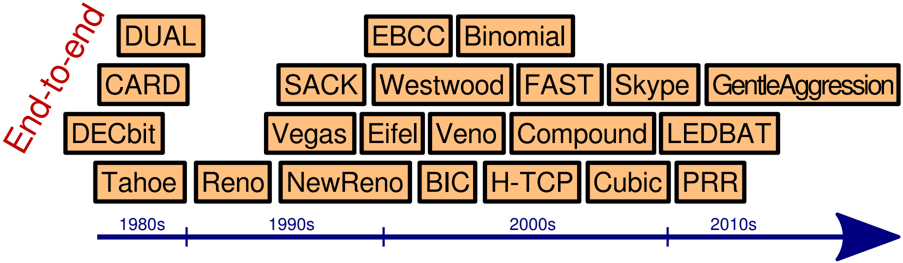

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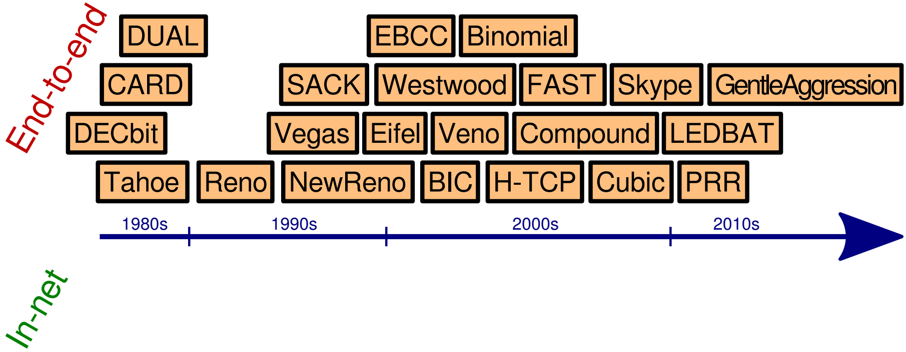

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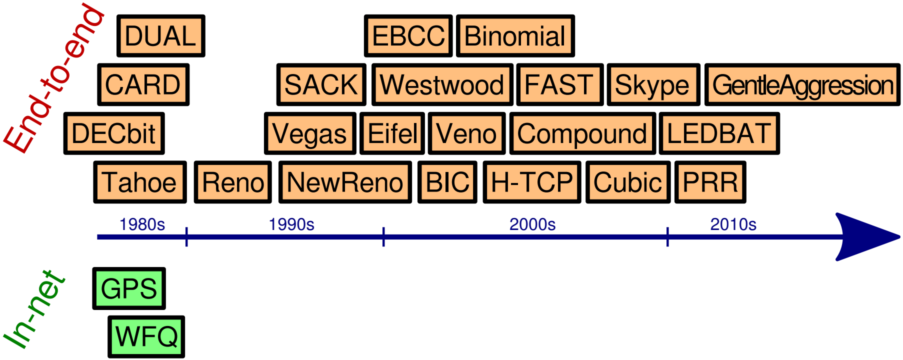

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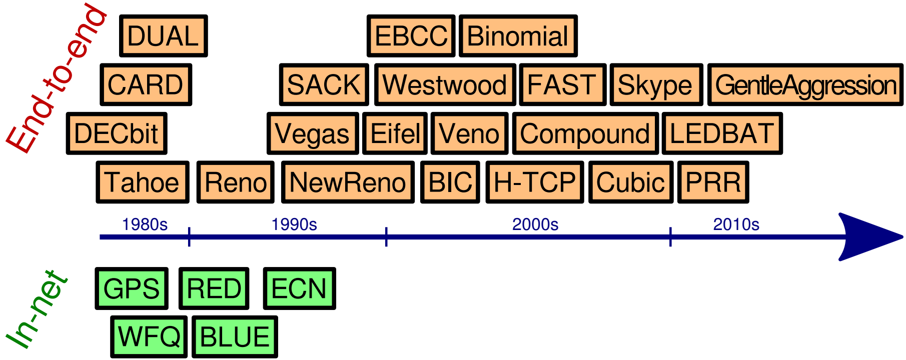

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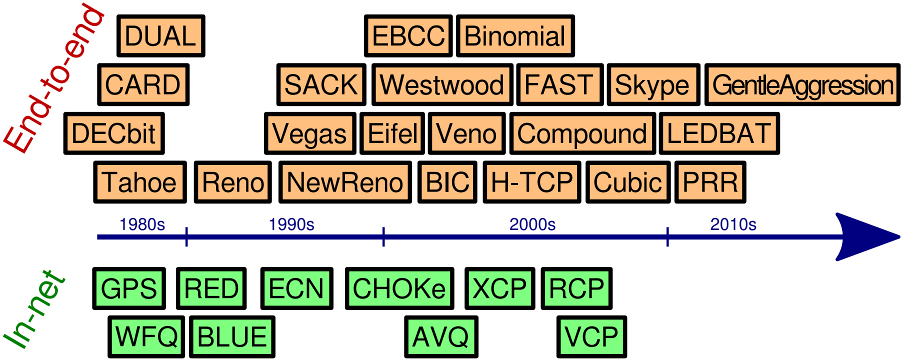

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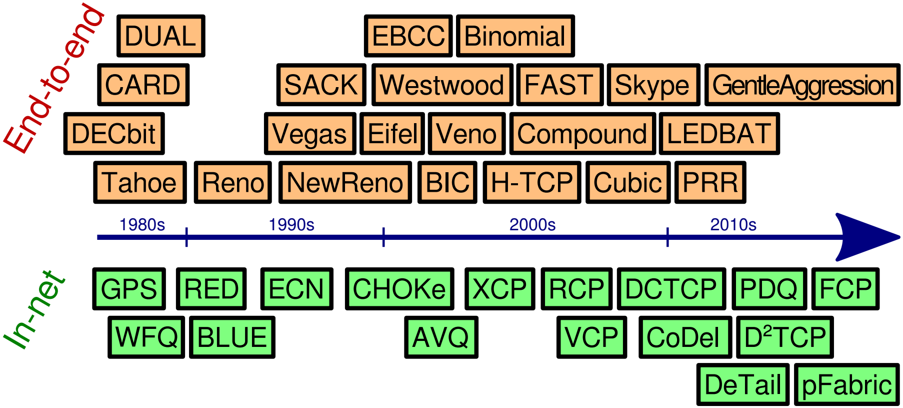


Declarative design

Systems with a **model** and a **mission**.

Explicitness in systems design

Model: explicit statement of assumptions about the problem

Mission: objective that the application wants

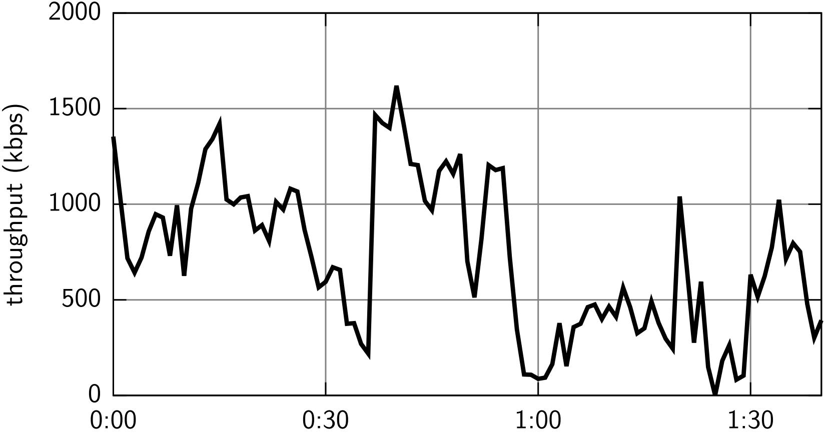
Explicit design considerations → **freedom to make changes**

Sprout: a transport protocol designed for variability

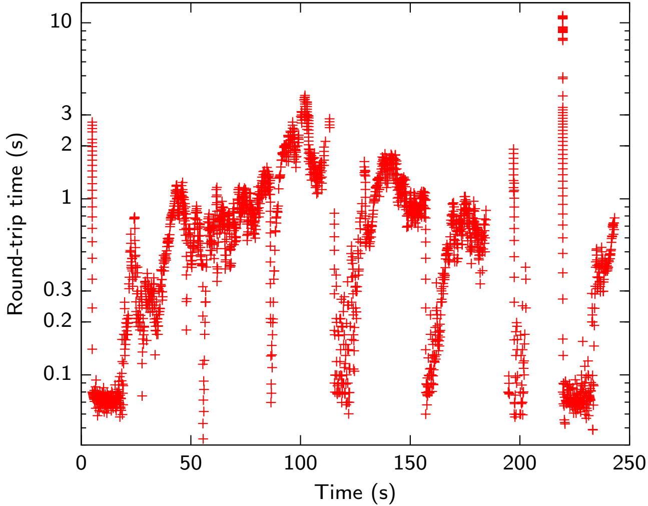
Observation:

Videoconferences perform poorly over cellular networks.

Verizon LTE uplink throughput



Verizon LTE ping delay during one TCP download

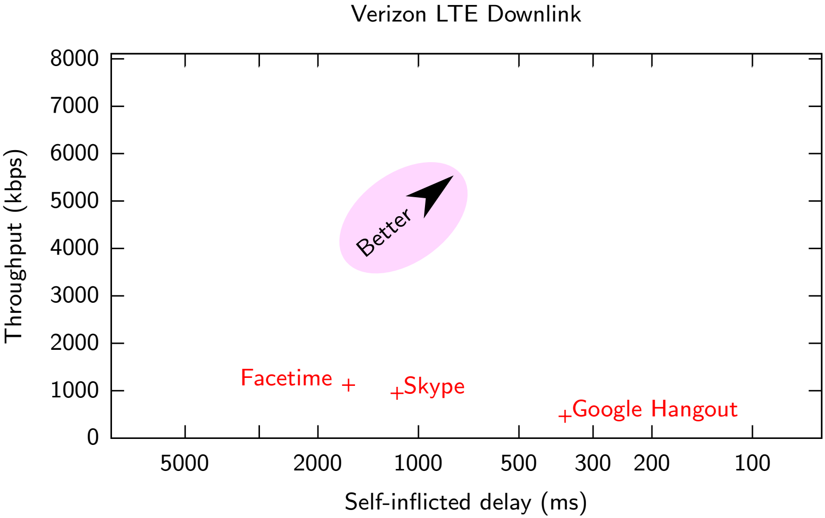


Interactive apps work poorly

- 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 Hangouts (Chrome on Windows 7)
  - Apple Facetime (OS X)

Skype's performance

Performance summary



What's wrong?

- Existing schemes **react** to congestion signals.
  - Packet loss.
  - Increase in round-trip time.
- Feedback comes too late.
- The killer: **self-inflicted queueing delay**.

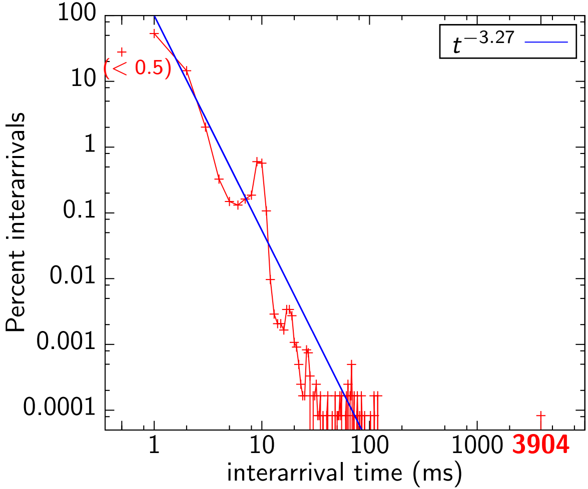
Sprout's **mission**

- Most throughput
- Bounded risk of delay > 100 ms

Bounded risk of delay

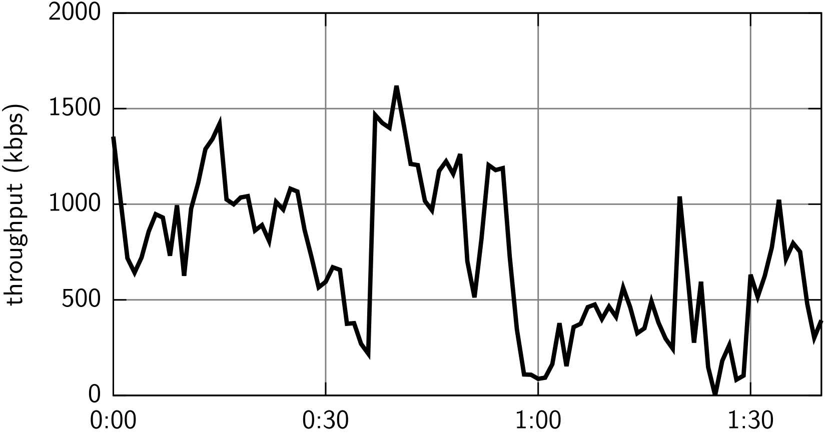
- **Model** variation in link speed
- **Infer** current link speed
- **Predict** future link speed
  - Don't wait for congestion
- **Control:** Send as much as possible, but require:
  - 95% chance all packets arrive within 100 ms

Model: packet deliveries looks like flicker noise

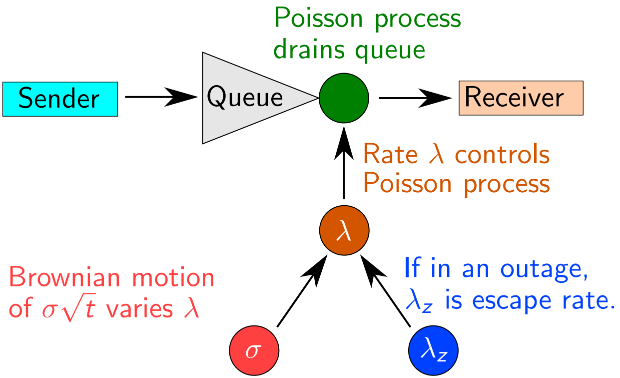


(Verizon LTE, phone stationary.)

Model: average rate looks like random walk



Sprout's **model**



Sprout's model parameters

Volatility σ: fixed @	$200 \frac{\text{pkts}/s}{\sqrt{s}}$
Expected outage time $1/\lambda_z$:	$1\ s$
Tick length (τ):	$20\ ms$
Forecast length:	$160\ ms$
Delay target:	$100\ ms$
Risk tolerance:	5%

All source code was **frozen before data collection began.**

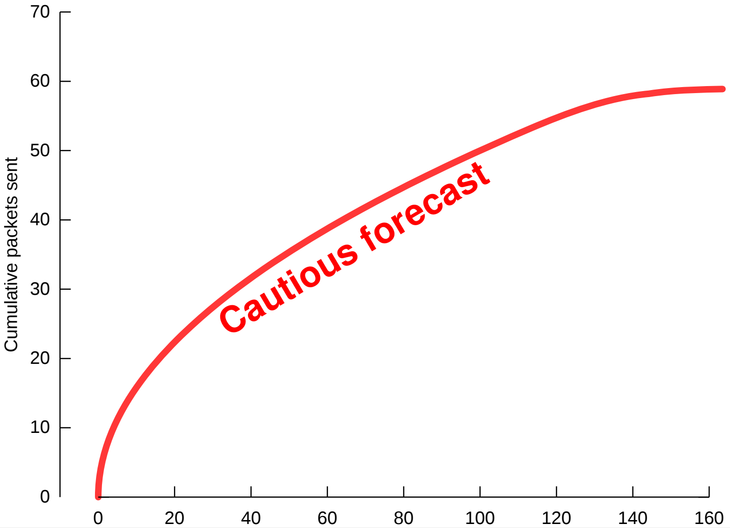
Infer: current link speed

- **Observe** packets received every τ
- **Update** P(λ)

Predict: future link speed

- **Evolve** model forward
- **Forecast** 5th percentile cumulative packets

Control: fill up 100 ms forecast window



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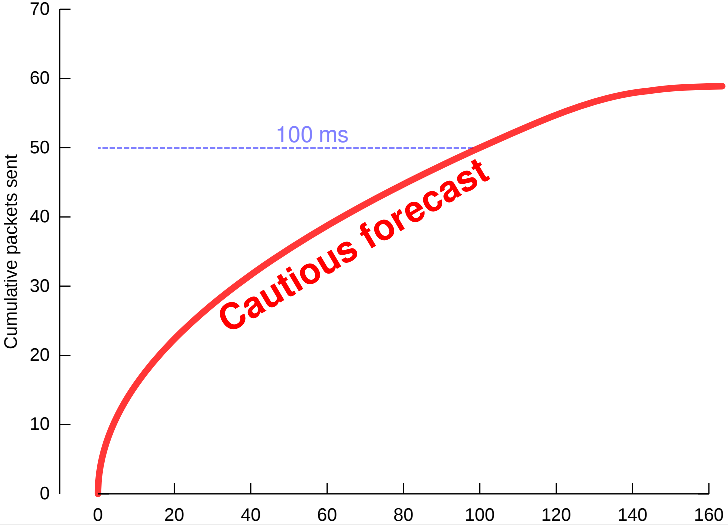

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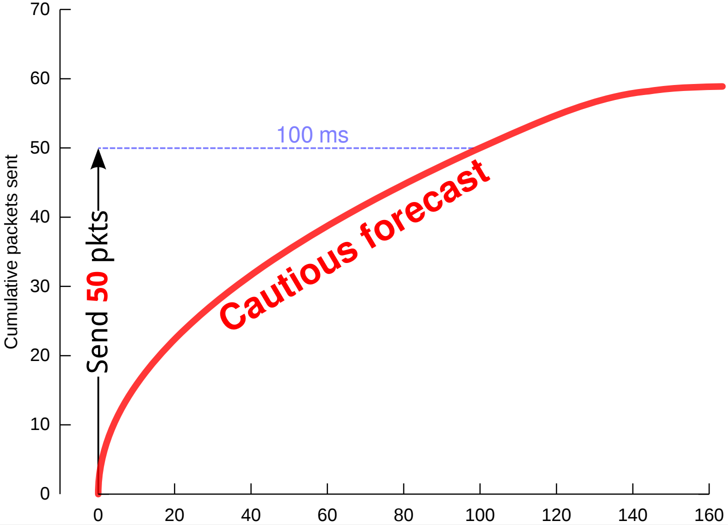

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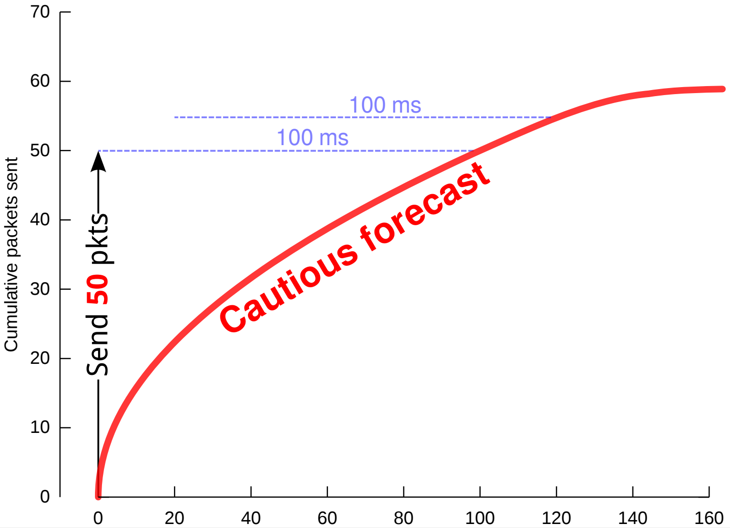

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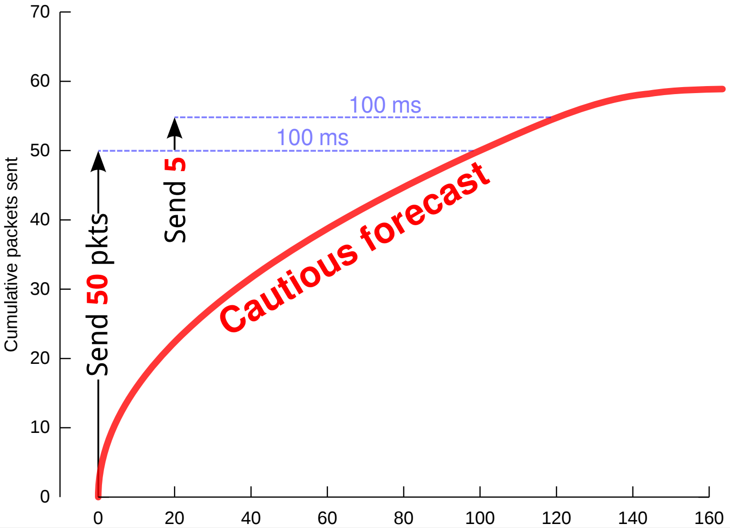

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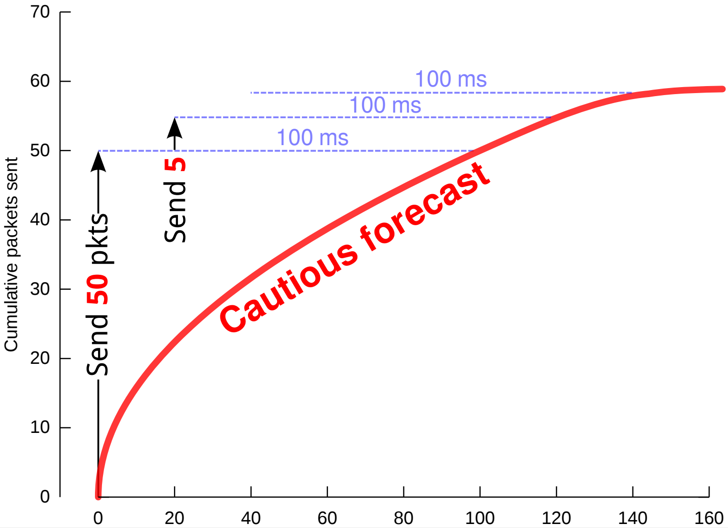

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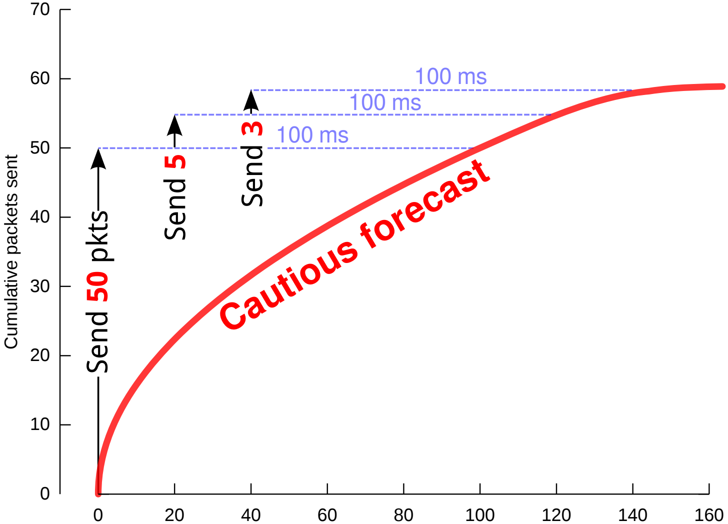
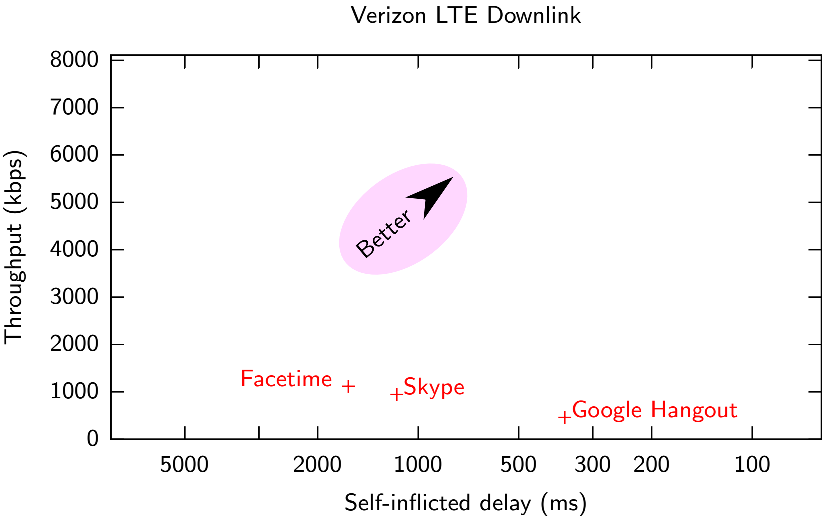
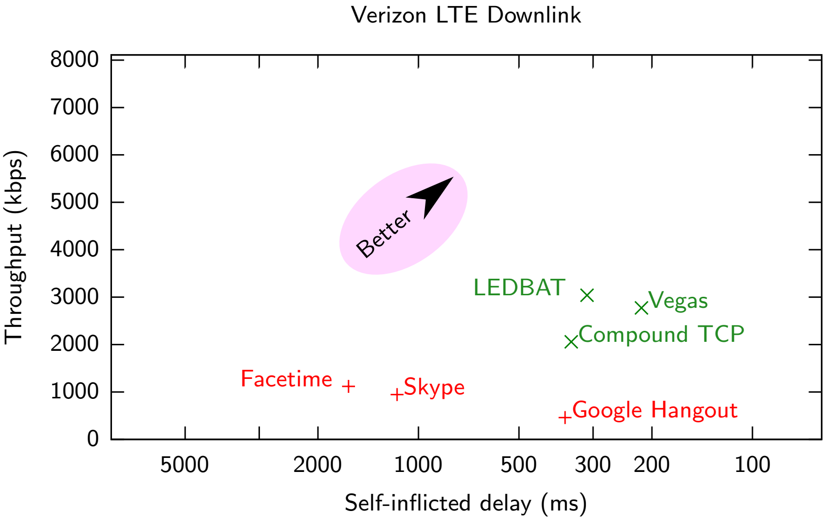


Sprout's results


Verizon LTE Downlink
Throughput (kbps)
8000
7000
6000
5000
4000
3000
2000
1000
0
Better
Facetime
Skype
Google Hangout
5000
2000
1000
500
300
200
100
Self-inflicted delay (ms)



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1000
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LEDBAT
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Compound TCP
Facetime
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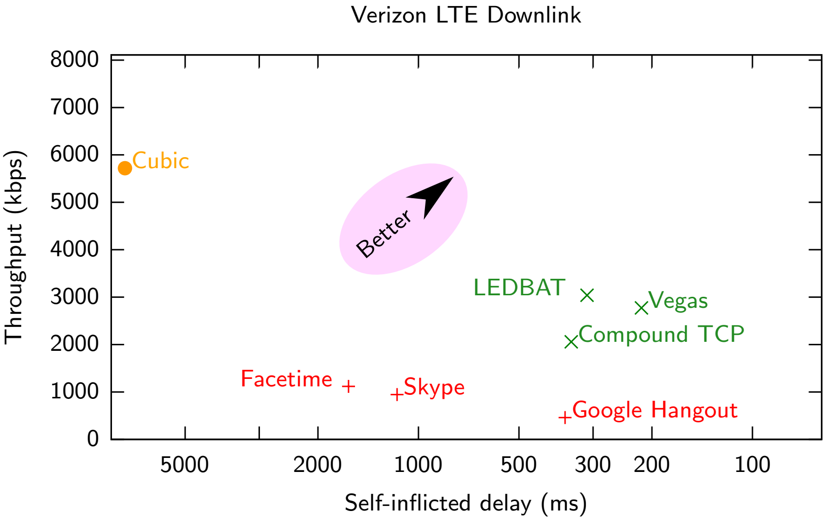
100
Self-inflicted delay (ms)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Self-inflicted delay (ms)
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Cubic
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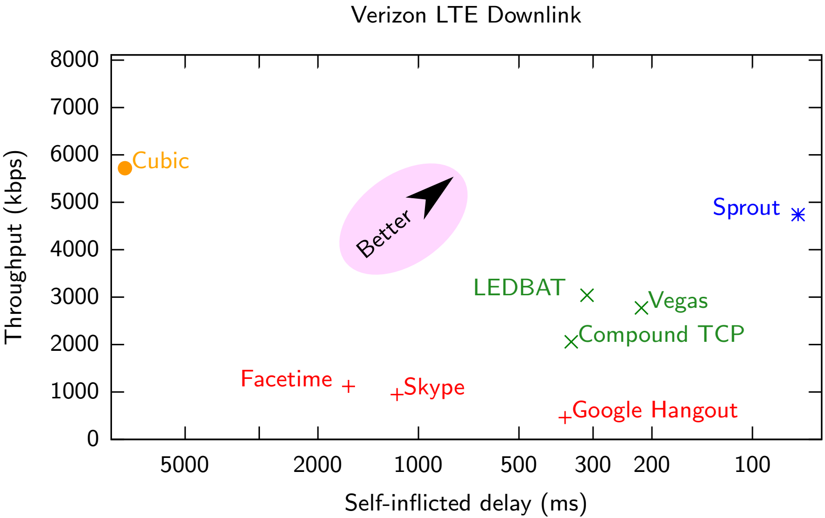
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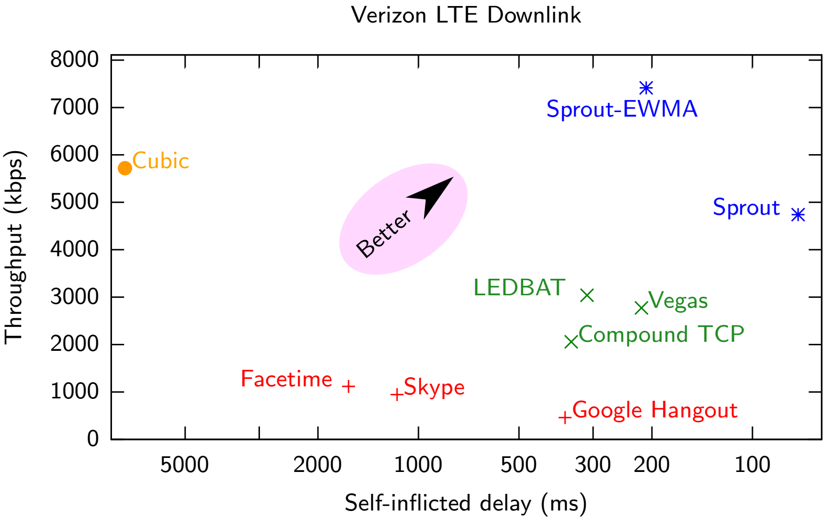
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Self-inflicted delay (ms)
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2000
1000
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300
200
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Sprout-EWMA
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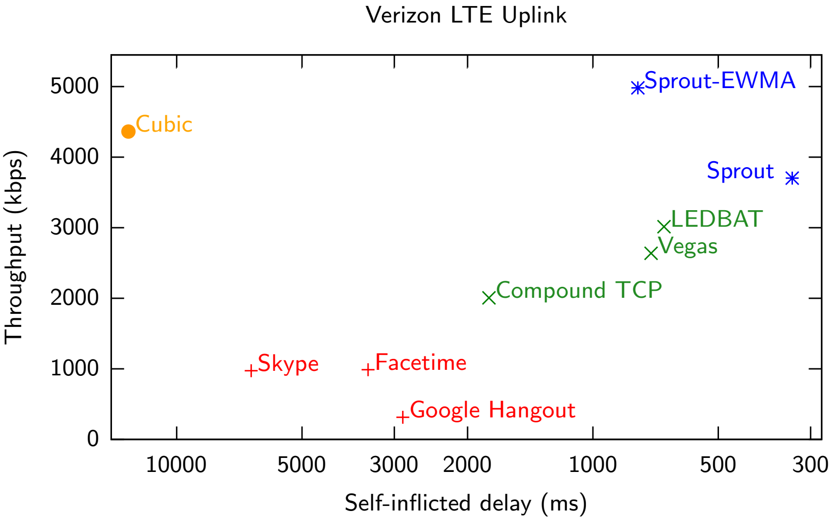
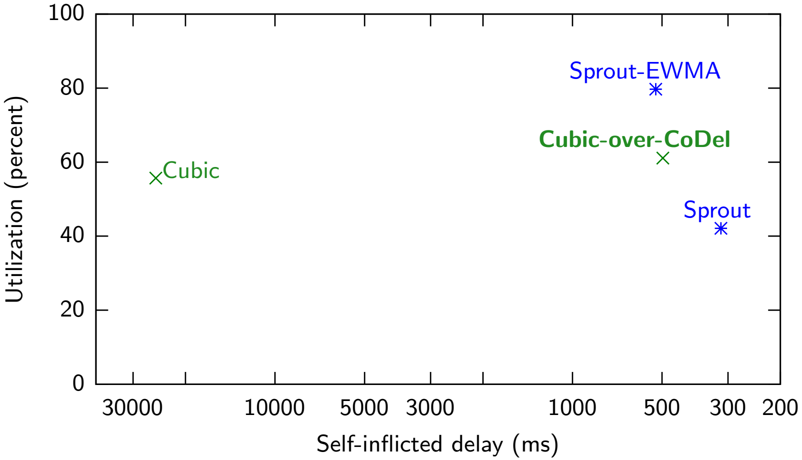

Verizon LTE Uplink
Throughput (kbps)
5000
4000
3000
2000
1000
0
10000
5000
3000
2000
1000
500
300
Self-inflicted delay (ms)
Sprout-EWMA
Cubic
Sprout
LEDBAT
Vegas
Compound TCP
Skype
Facetime
Google Hangout

Overall results on 8 links

Verizon 3G/LTE, AT&T LTE, T-Mobile 3G uplink and downlink:

Sprout vs.	Avg. speedup	Delay reduction
Skype	2.2×	7.9×
Hangout	4.4×	7.2×
Facetime	1.9×	8.7×
Compound	1.3×	4.8×
TCP Vegas	1.1×	2.1×
LEDBAT	Same	2.8×
Cubic	0.91×	79×

Sprout is end-to-end, but comparable to in-net control



M.I.T. 6.829 contest (March–April 2013)

- Turnkey network emulator, evaluation
- Sender, receiver run in Linux containers
- **Mission**: maximize throughput/delay
- 4th prize: $20
- 3rd prize: $30
- 2nd prize: $40
- (If beat Sprout) 1st prize:

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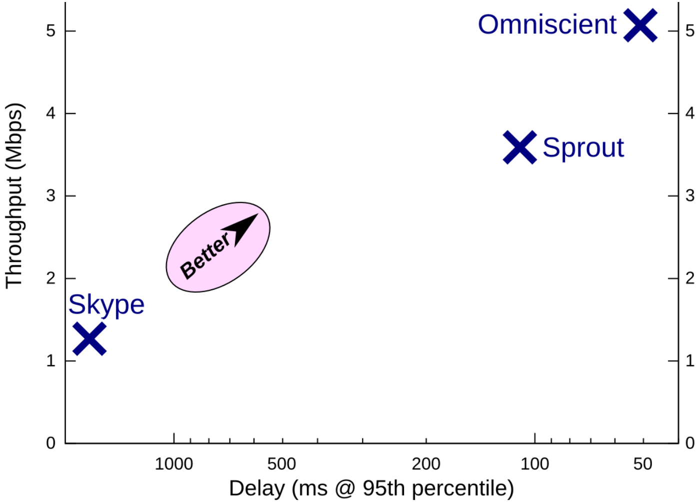
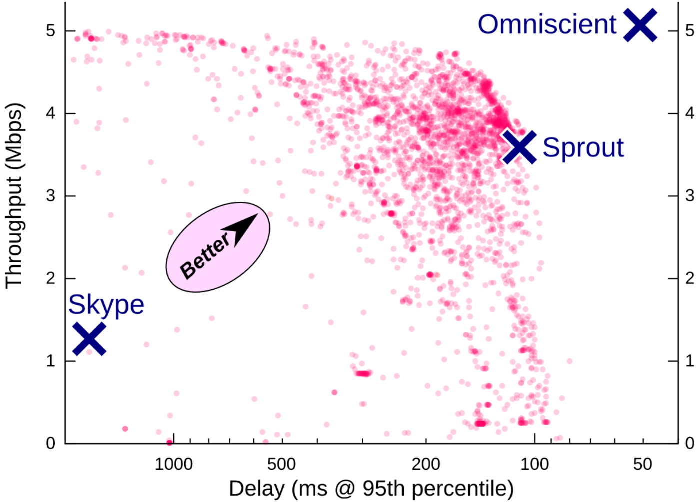
Anirudh Sivaraman, KW, Pauline Varley, Somak Das, Joshua Ma, Ameesh Goyal, João Batalha, and Hari Balakrishnan, **Protocol Design Contests**, *in submission*

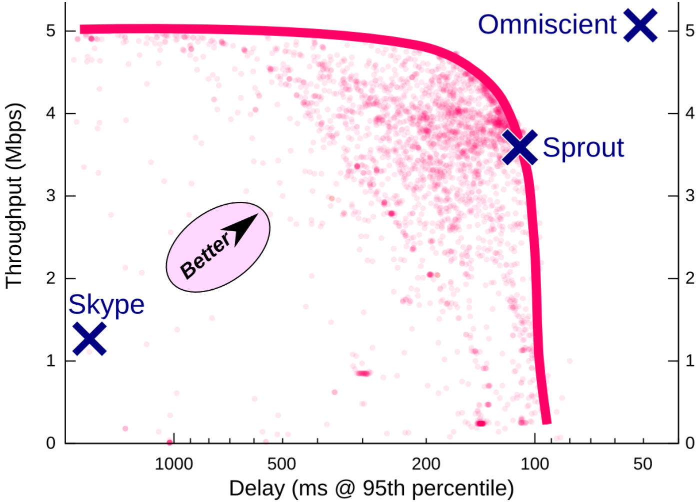
Baseline


Omniscient
Sprout
Skype
Better
Throughput (Mbps)
0
1
2
3
4
5
1000
500
200
100
50
Delay (ms @ 95th percentile)

Land of 3,000 student protocols



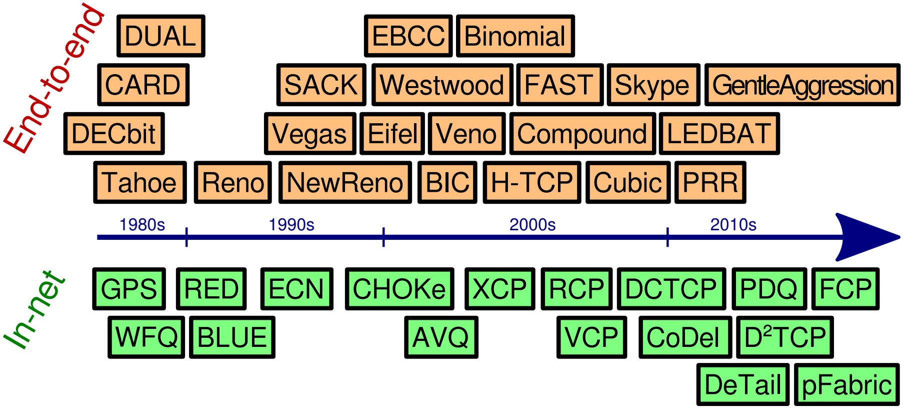
Sprout was on the frontier



Limitations

- Sprout wants to control all of the traffic on a queue.
  - Cells generally have **per-user** queues. . .
  - . . . but Wi-Fi and wired networks usually don't.
- What if cell link *isn't* the bottleneck?
- Assumption: application always has data to send

Sprout's mark



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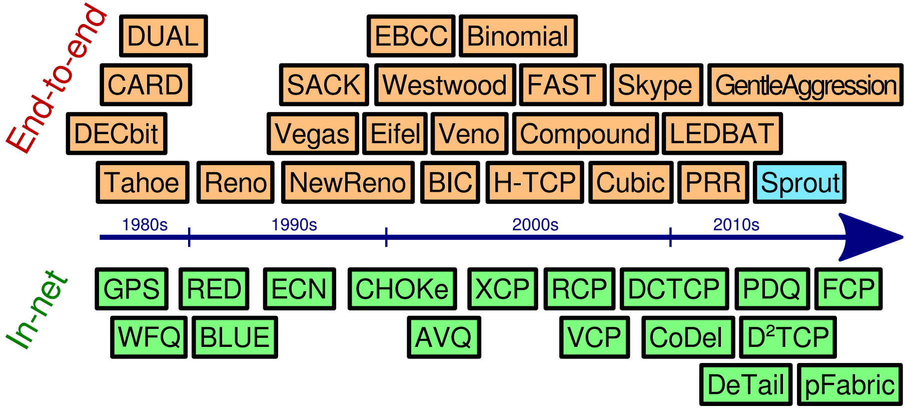

Now that we have 40+ algorithms...

- Sprout for cellular networks?
- Wireless-TCP for Wi-Fi?
- High-BDP-TCP for transoceanic links?
- Datacenter-TCP for datacenters?
- CoDel for cable modems?
- **TBA-TCP for tomorrow's networks?**

Rational choice of scheme is challenging

$\boxed{\text{Cubic}}$ **vs.** $\boxed{\text{Compound}}$

- Different missions?
- Different assumptions about network?
- One scheme just plain better?

Networks constrained by a fuzzy idea of TCP's assumptions

- Mask stochastic loss
- Bufferbloat
- Mask out-of-order delivery
- No parallel/multipath routing

Advice for Internet Subnetwork Designers (RFC 3819) is 21,000 words!

Apps hack around TCP

- Open lots of flows
- Goose slow start
- Add pacing
- Give up and do it yourself

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Chrome (QUIC)
BitTorrent (μTP)
Mosh (SSP)
IBM Aspera (fasp)

Idea: computer-generated protocols

Transport layer should adapt to **whatever**:

- network does
- application wants

Idea: computer-generated protocols

Transport layer should adapt to **whatever**:

- network does (**model**)
- application wants (**mission**)

What we built

Remy: a program that generates congestion-control schemes offline

Input:

- Assumptions about network and workload (**model**)
- Application's objective (**mission**)

Output: CC algorithm for a TCP sender (RemyCC)

Time: hours to days

The basic question of congestion control

At this moment, do I:

- send a packet
- not send a packet?

Missions of congestion control

Maximize

- $\sum_i \log\left[\text{throughput}_i\right]$ (proportionally fair throughput)

Missions of congestion control

Maximize

- $$\sum_i \log\left[\text{throughput}_i\right]$$ (proportionally fair throughput)
- $$\sum_i \log\left[\frac{\text{throughput}_i}{\text{delay}_i}\right]$$ (proportionally fair throughput/delay)

Missions of congestion control

Maximize

- $$\sum_i \log\left[\text{throughput}_i\right]$$ (proportionally fair throughput)
- $$\sum_i \log\left[\frac{\text{throughput}_i}{(\text{delay}_i)^{\delta}}\right]$$ (proportionally fair throughput/delay)

Missions of congestion control

Maximize

- $\sum_i \log\left[\text{throughput}_i\right]$ (proportionally fair throughput)
- $\sum_i \log\left[\frac{\text{throughput}_i}{\left(\text{delay}_i\right)^{\delta}}\right]$ (proportionally fair throughput/delay)
- $\min_i \text{throughput}_i$ (max-min throughput)

Minimize

- mean flow completion time
- page load time

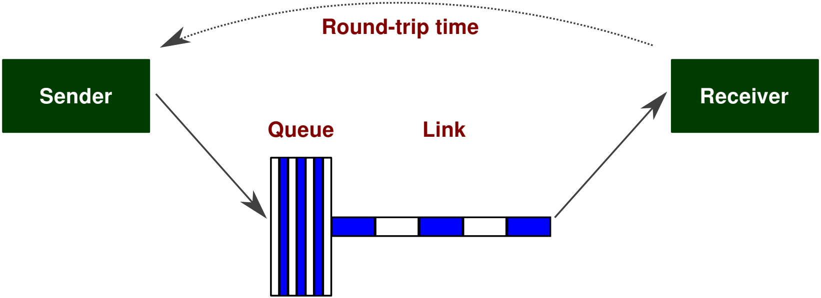
Prevent

- pathological behavior
- congestion collapse

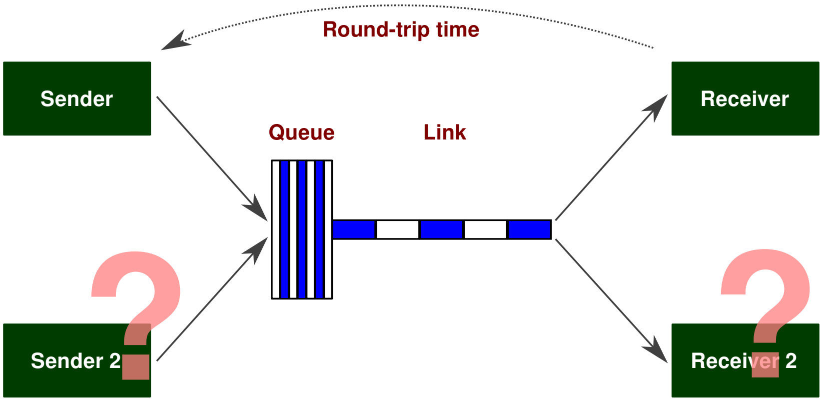
Encoding the designer's prior assumptions

- **Model** of network uncertainty
  - Link speed distribution
  - Delay distribution
  - Topology distribution
- **Model** of workload
  - Web browsing
  - MapReduce
  - videoconferencing
  - streaming video (YouTube/Netflix)

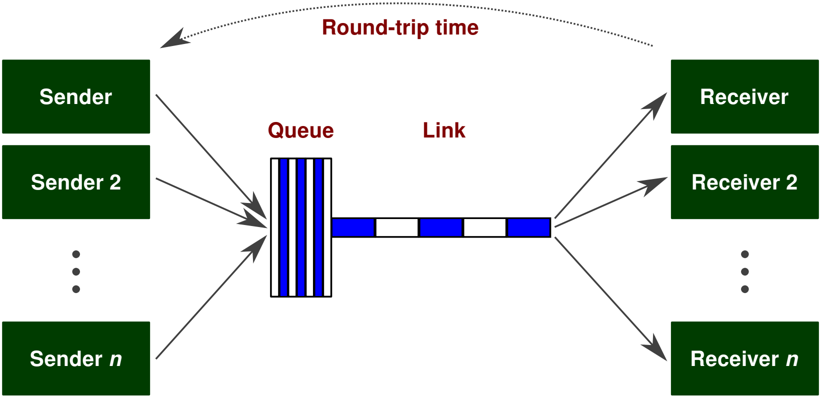
Dumbbell network



Dumbbell network



Dumbbell network



Superrational congestion control

At this moment,* do I:

- send a packet
- not send a packet?

Superrational congestion control

At this moment,* do I:

- send a packet
- not send a packet?

* Assuming every node is running the same algorithm.

Remy: tractable search for best policy

- Best decision given all history: not tractable
- Instead, **summarize the history**

A RemyCC tracks four congestion signals

r_ewma$_\alpha$: **short-term** moving average of interval between acks
"How fast are packets arriving (now)?"

r_ewma$_\beta$: **long-term** moving average of same
"How fast are packets arriving (smoothed)?"

s_ewma: moving average of interval between acked timestamps
"How fast was I sending?"

rtt_ratio: ratio of last RTT to smallest RTT so far
"How long is the queue?"

Why these four features?

- We can measure the benefit of each!
- Removing any one hurts
  - losing r_ewma_α hurts the most
- More signals increase search time
- ...but others might help on some networks

A RemyCC maps each state to an action

$$\textsc{RemyCC}(\mathit{r\_ewma}_{\alpha\beta}, \mathit{s\_ewma}, \mathit{rtt\_ratio}) \rightarrow \langle m, b, \tau \rangle$$

m	Multiple to congestion window
b	Increment to congestion window
τ	Minimum interval between two outgoing packets

Runtime for a RemyCC

On ack:

- $\langle m, b, \tau \rangle \leftarrow \textsc{RemyCC}(r\_ewma_{\alpha\beta}, s\_ewma, rtt\_ratio)$
- $\texttt{cwnd} \leftarrow m \cdot \texttt{cwnd} + b$

Send packet if:

- $\texttt{cwnd} > \texttt{FlightSize}$, and
- last packet sent $> \tau$ ago

Remy's job

Find piecewise-continuous $\textsc{RemyCC}()$ that optimizes expected value of objective function

Remy example: 2D state space

On ack:

$$\langle m, b, \tau \rangle \leftarrow \textsc{RemyCC}(\mathit{s\_ewma}, \mathit{r\_ewma}_{\alpha}, \quad \mathit{r\_ewma}_{\beta}, \mathit{rtt\_ratio} \quad)$$

Remy example: 2D state space

On ack:

$\langle m, b, \tau \rangle \leftarrow \textsc{RemyCC}(s\_ewma, r\_ewma_{\alpha},$ [redacted]$)$

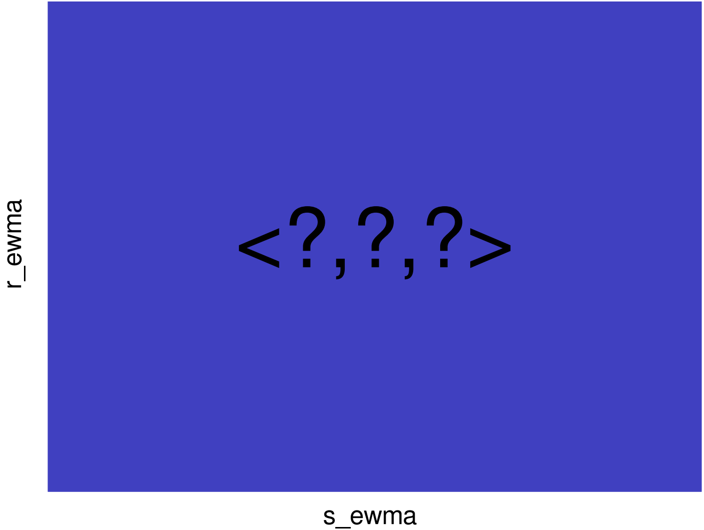
Remy example: **model**

Quantity	Distribution	Units
Link speed	Uniform(10, 20)	Mbps
RTT	Uniform(100, 200)	ms
n	Uniform(1, 16)	
“On” process “Off” process	$\exp[\mu = 5]$ same	seconds

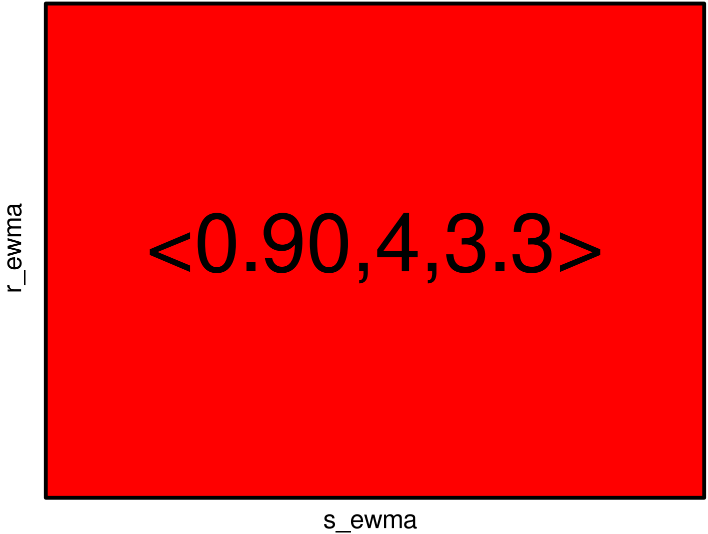
Remy example: **mission**

$$\sum_i \log \left[\frac{\text{throughput}_i}{\text{delay}_i} \right]$$

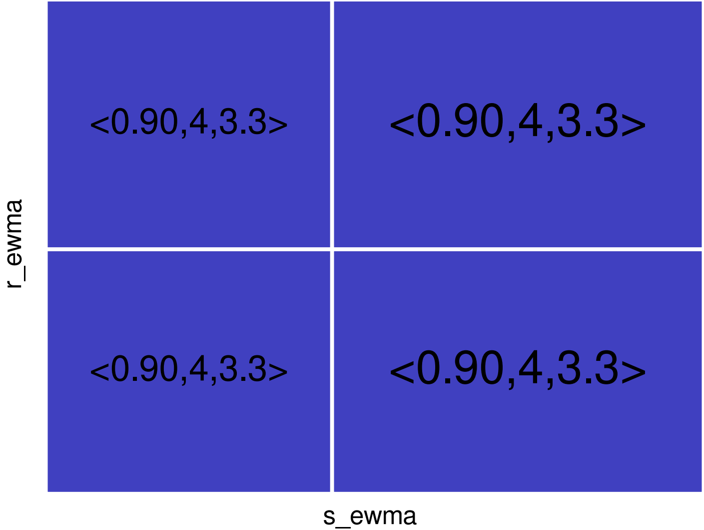
One action for all states. Find the best value.



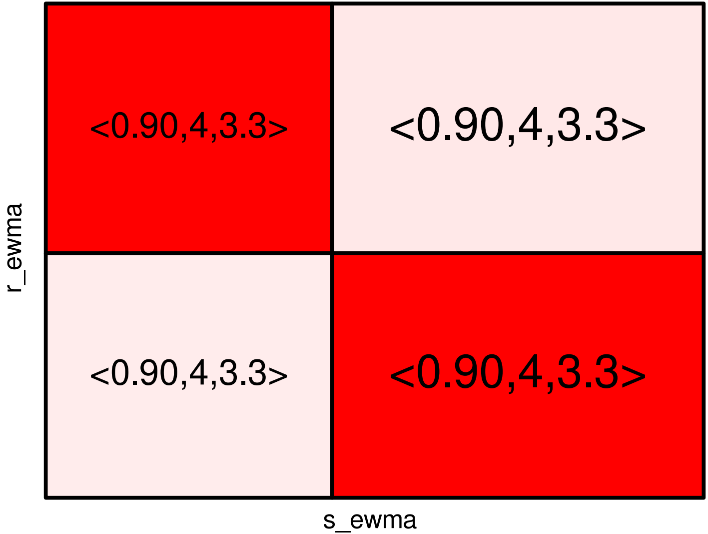
The best (single) action. Now split it on median.



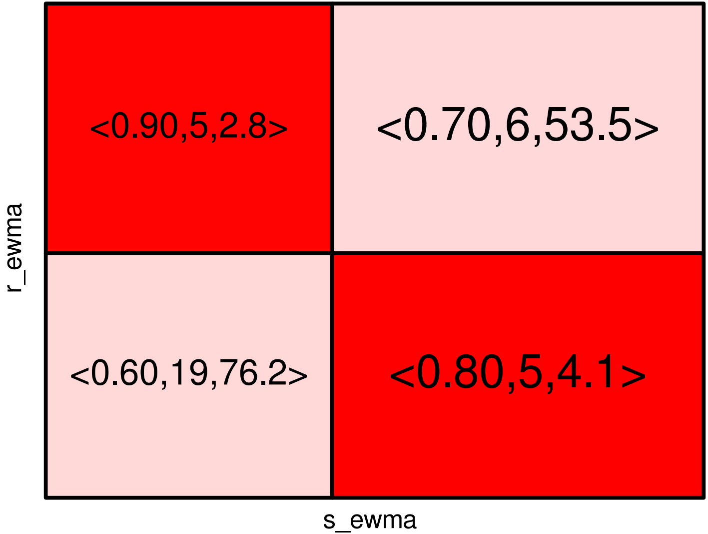
Simulate



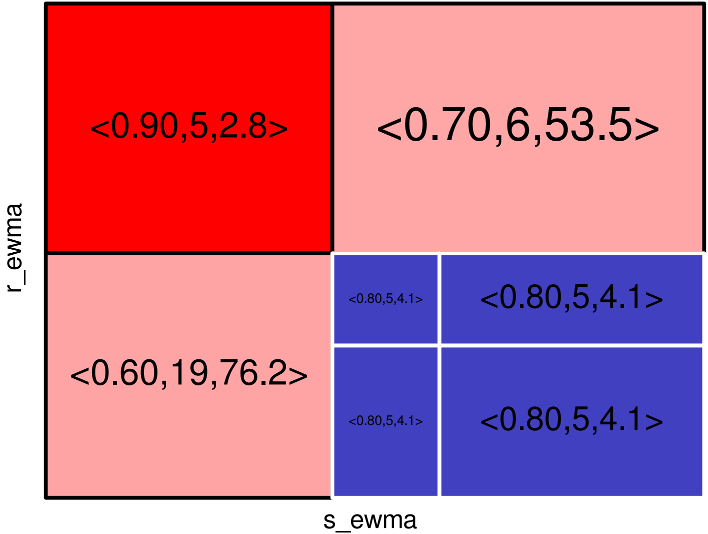
Optimize each of the new actions



Now split the most-used rule



Simulate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r_ewma
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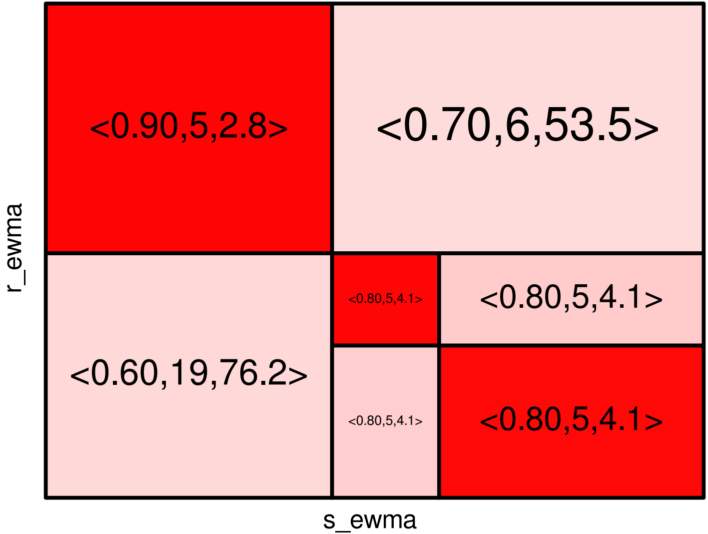
Optimize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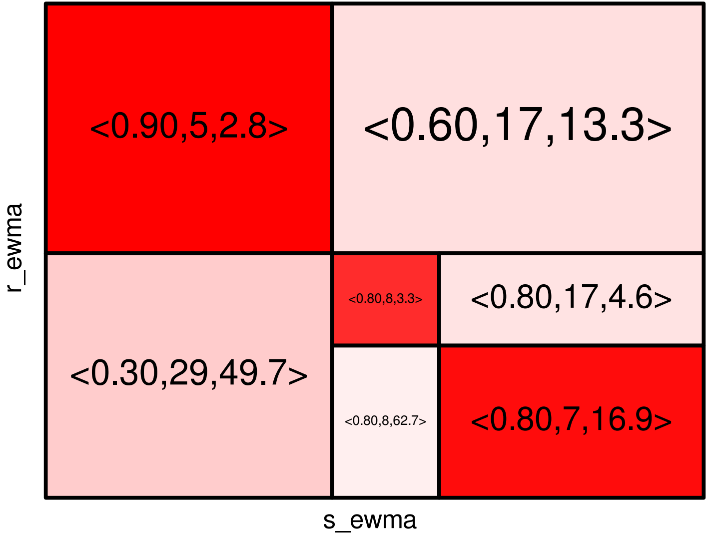
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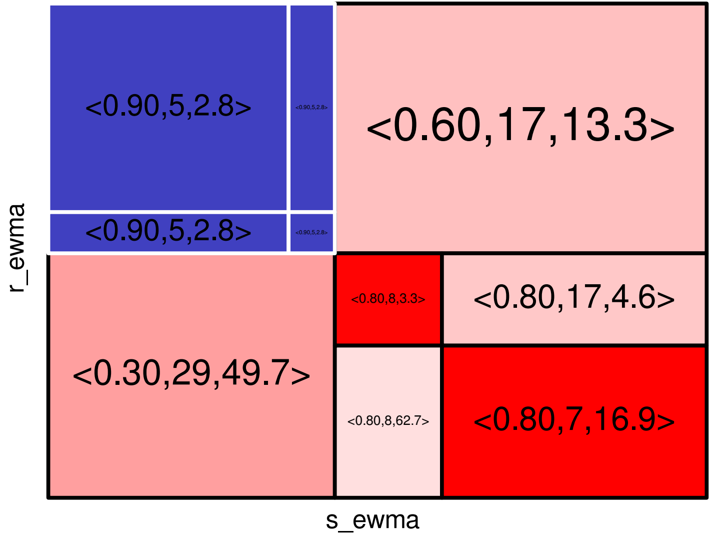
Simulate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r_ewma
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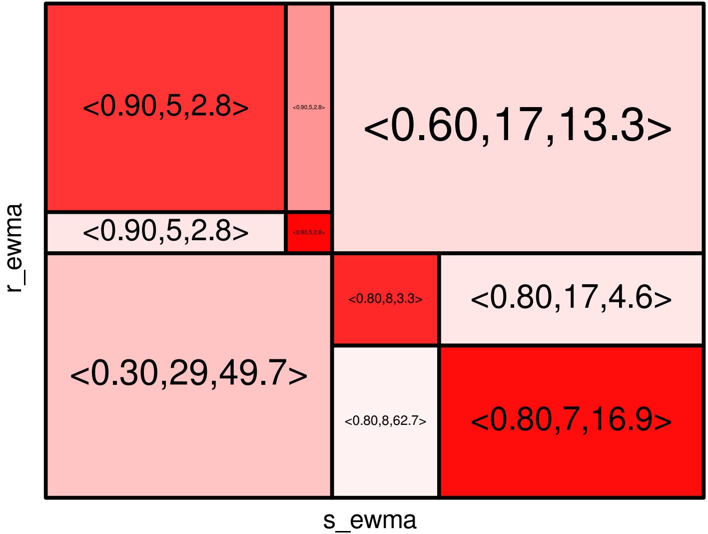
Optimize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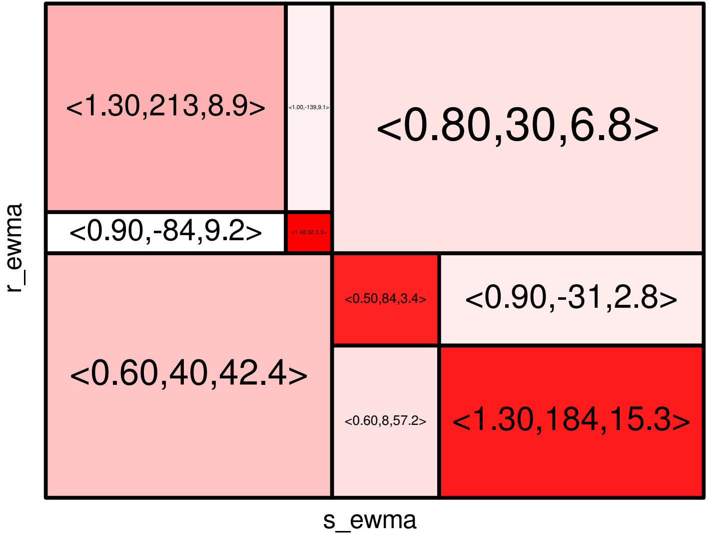
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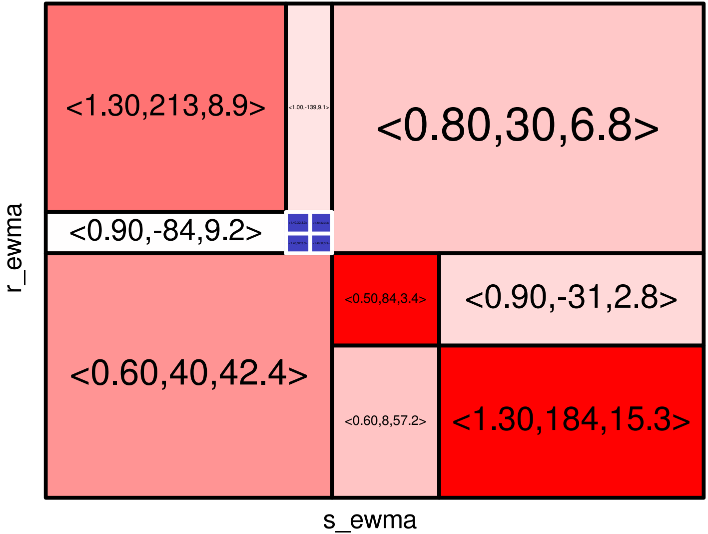
Simulate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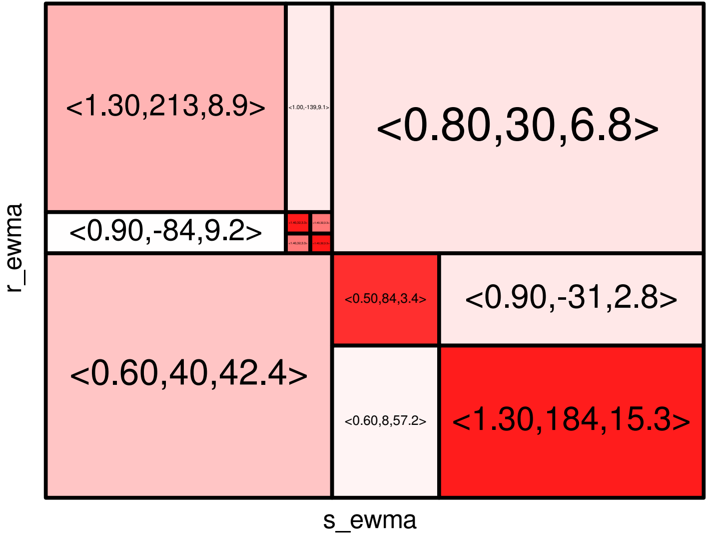
Optimize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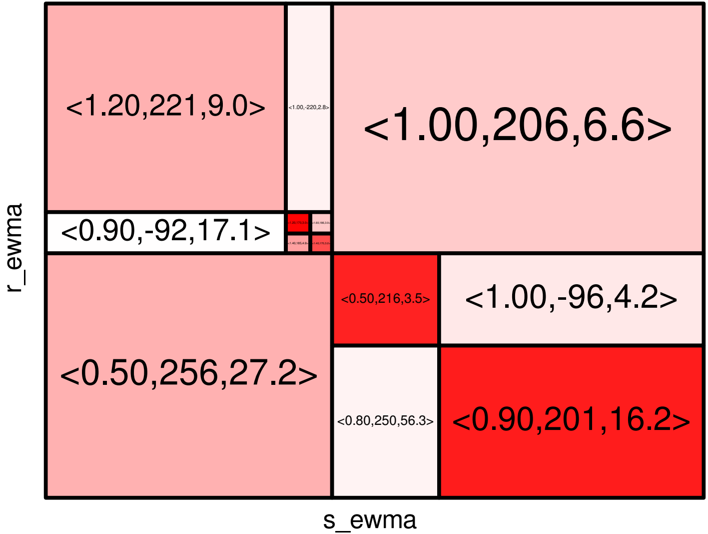
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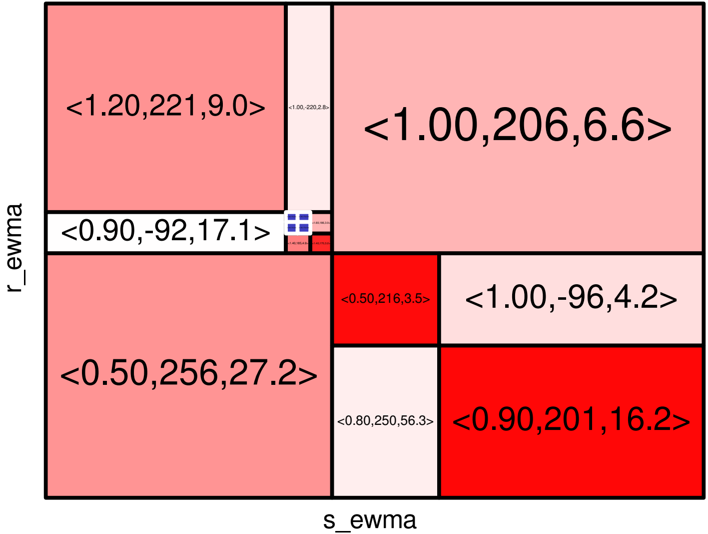
s_ewma

Simulate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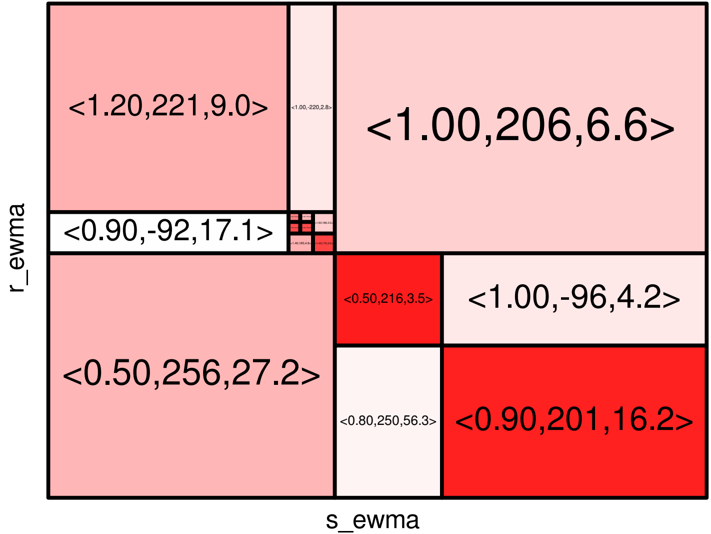
r_ewma
s_ewma

Optimize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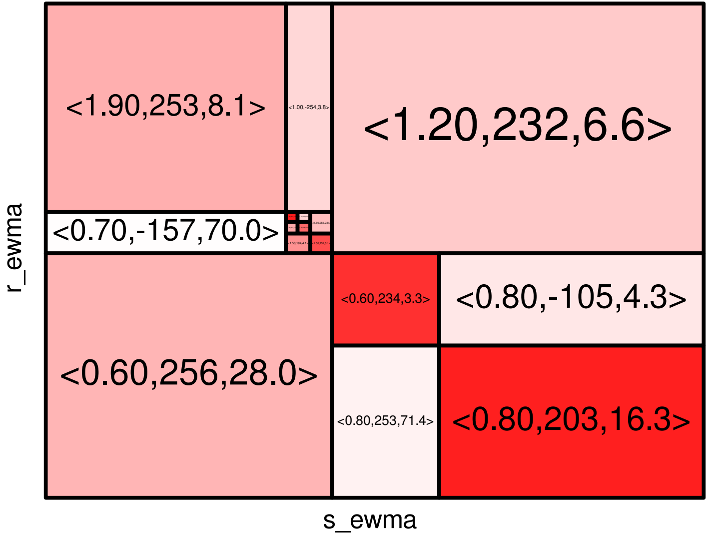
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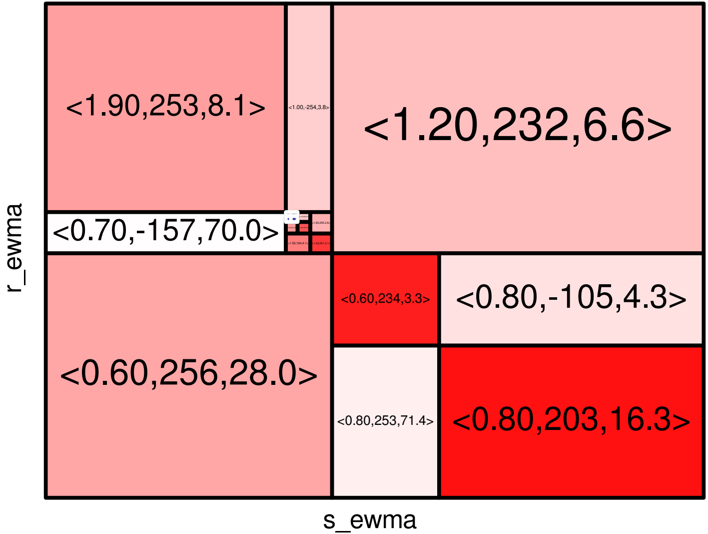
s_ewma

Simulate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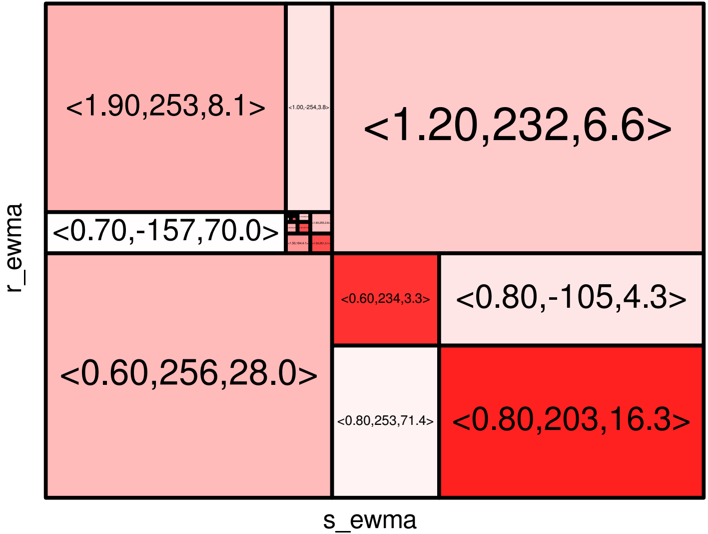
Optimize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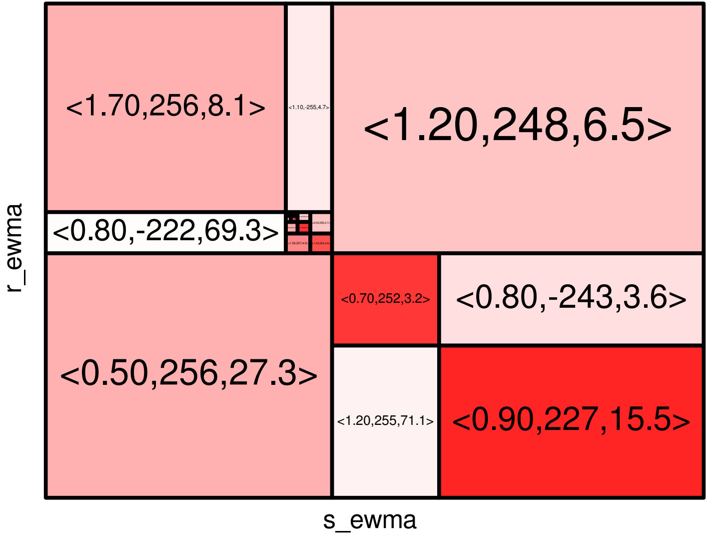
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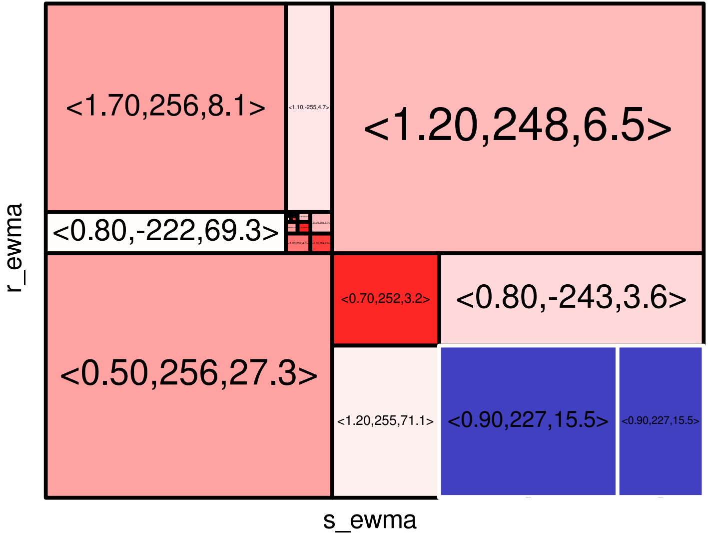
Simulate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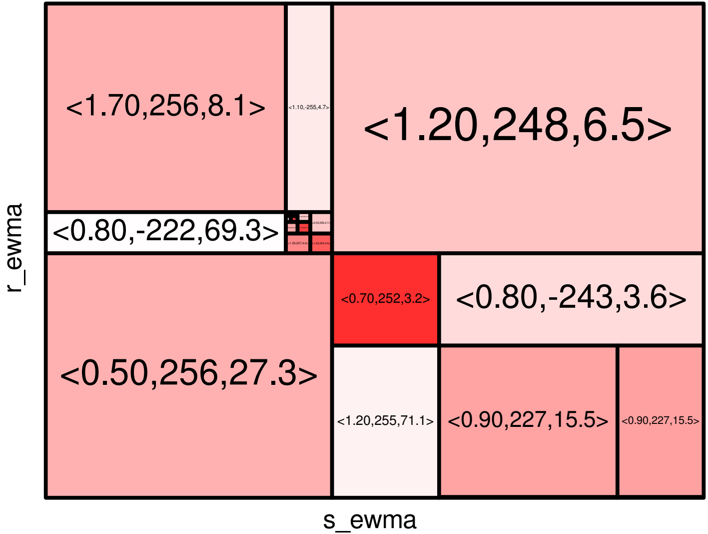
Optimize



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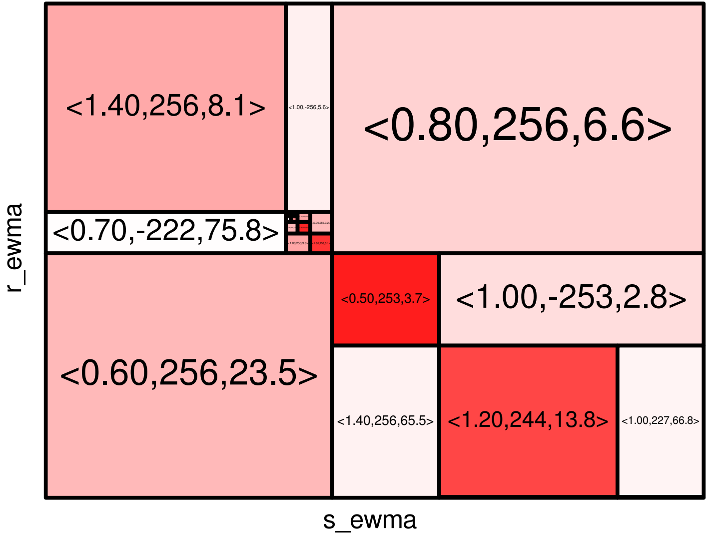
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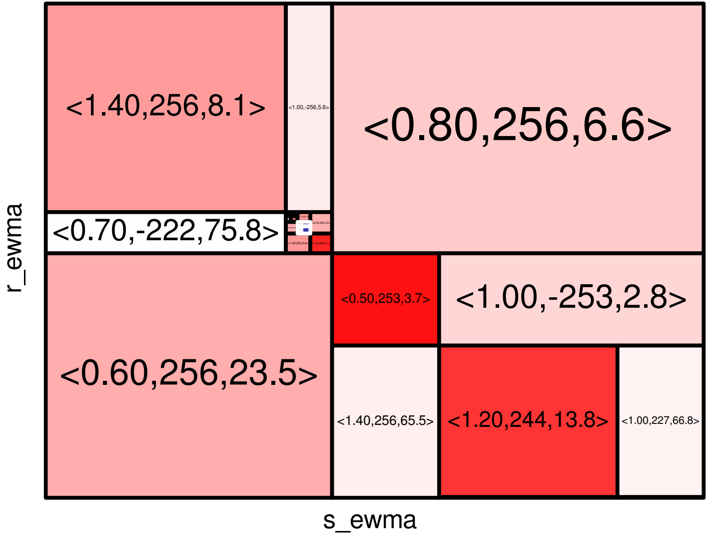
Simulate



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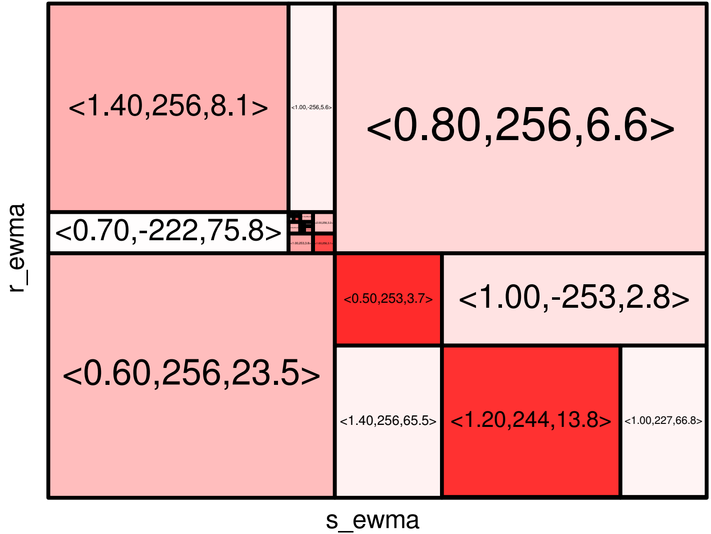
Optimize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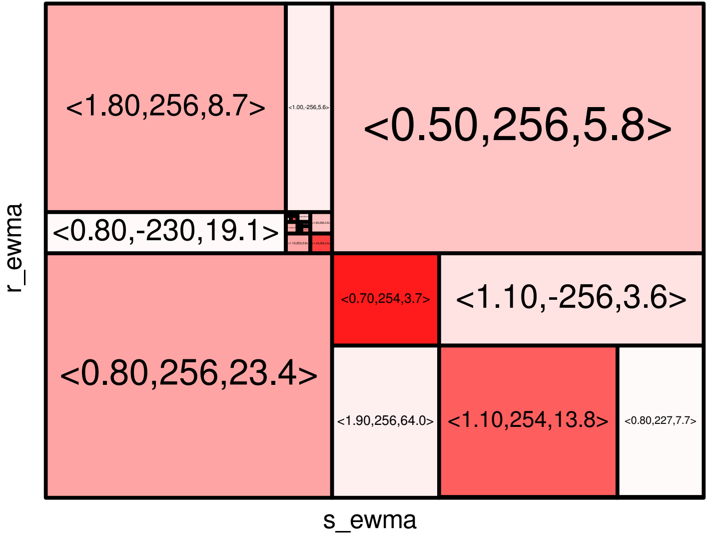
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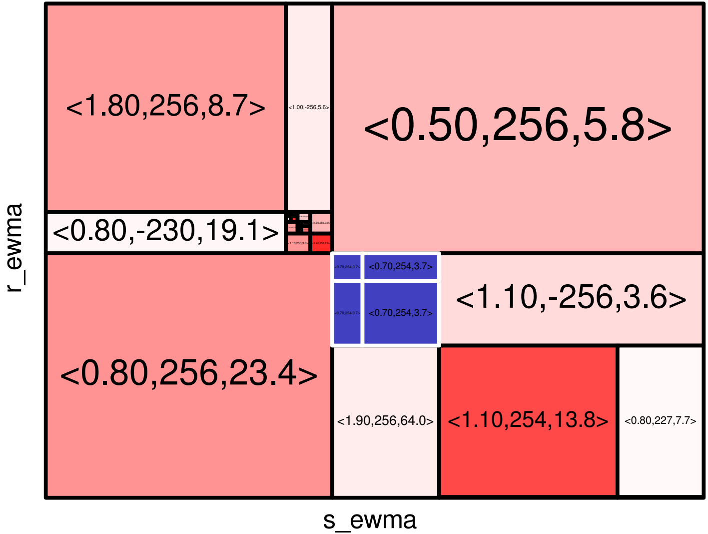
Simulate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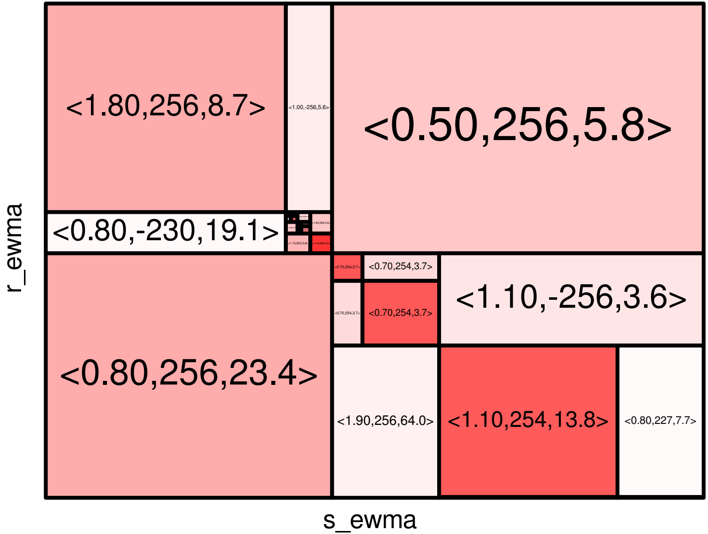
Optimize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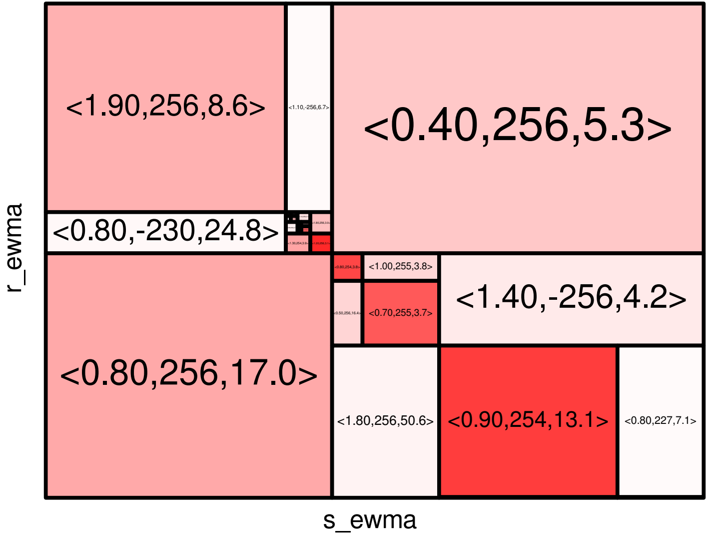
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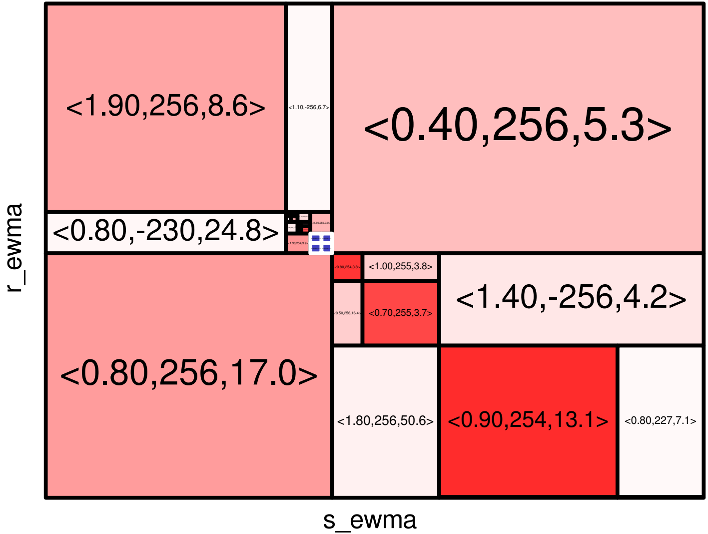
Simulate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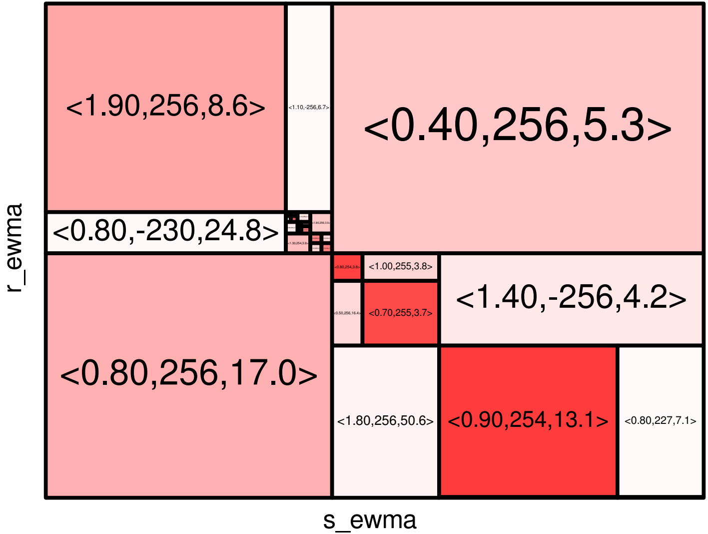
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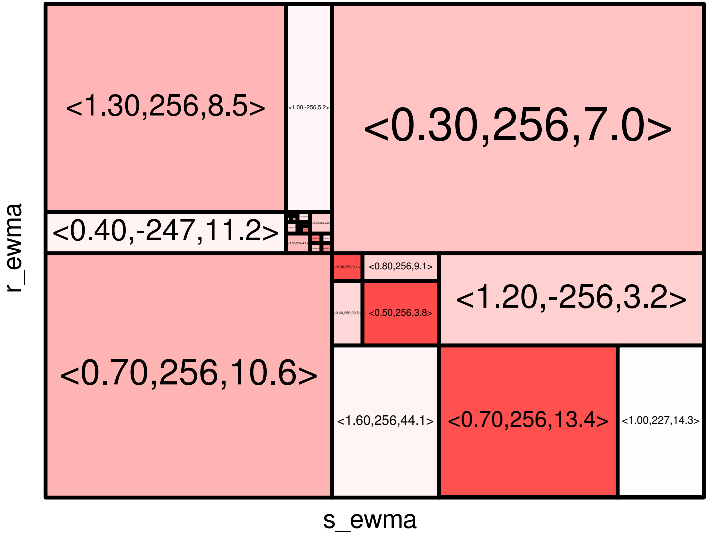

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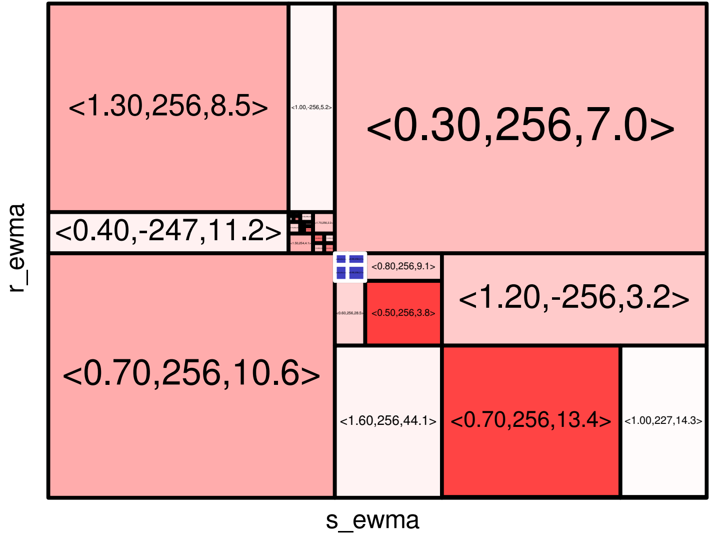
Simulate



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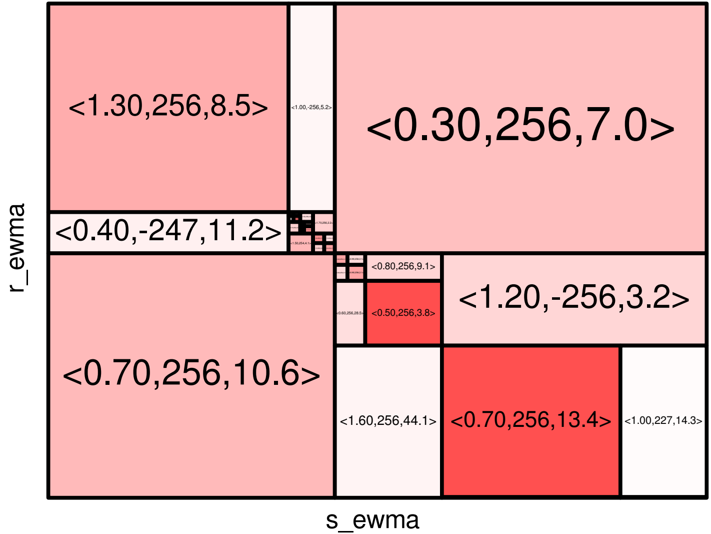
Optimize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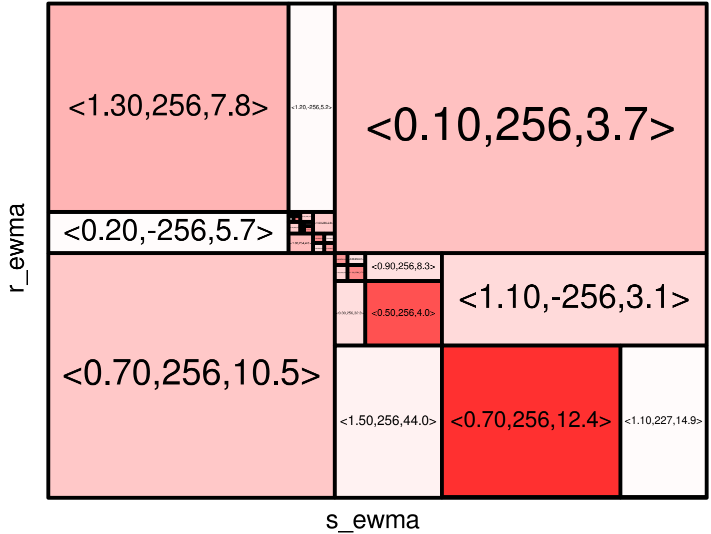
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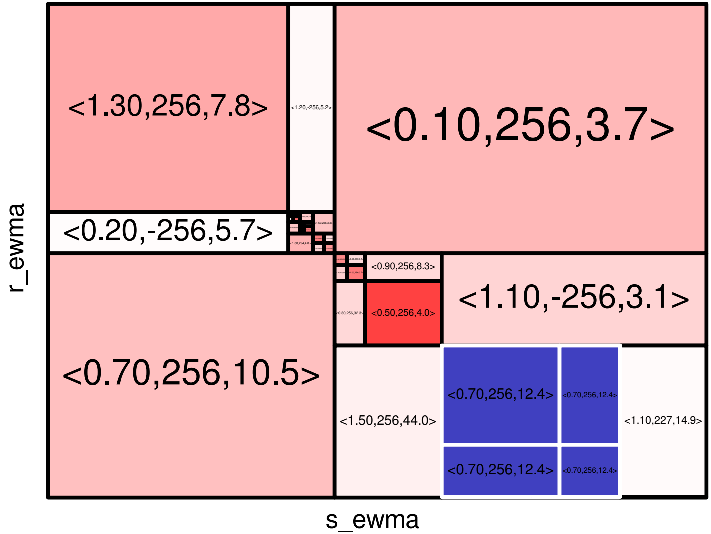
Simulate



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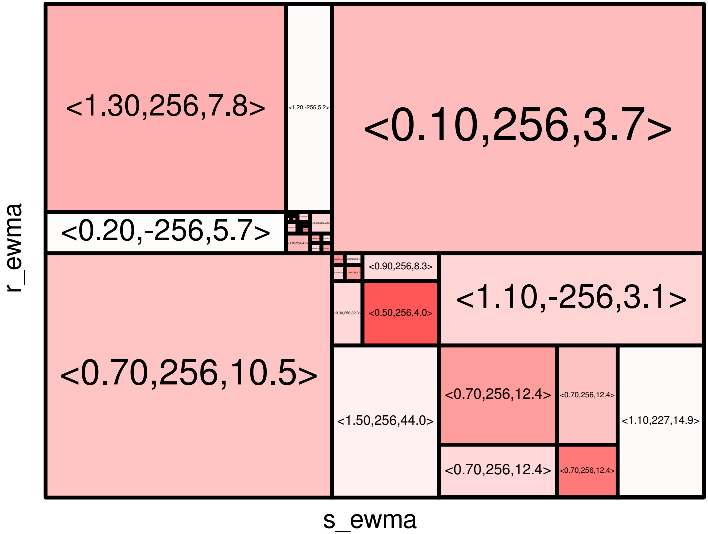
Optimize



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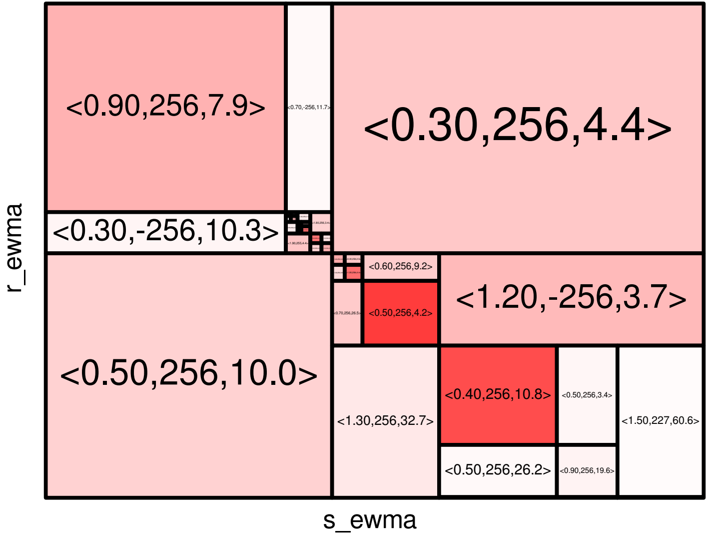
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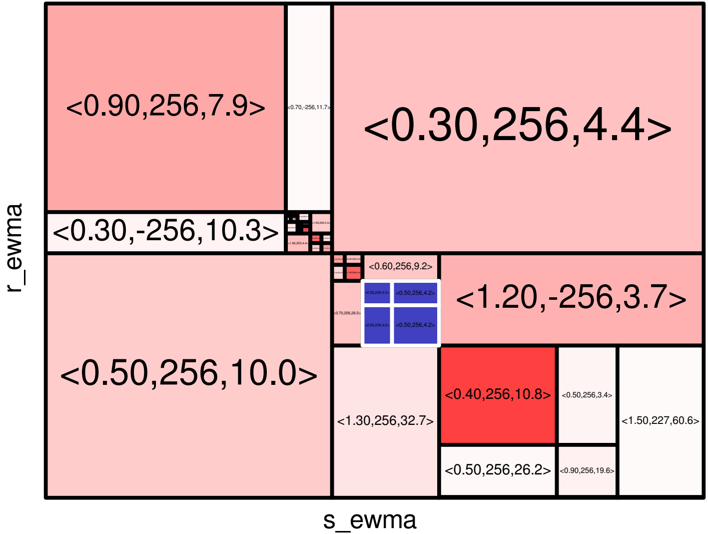
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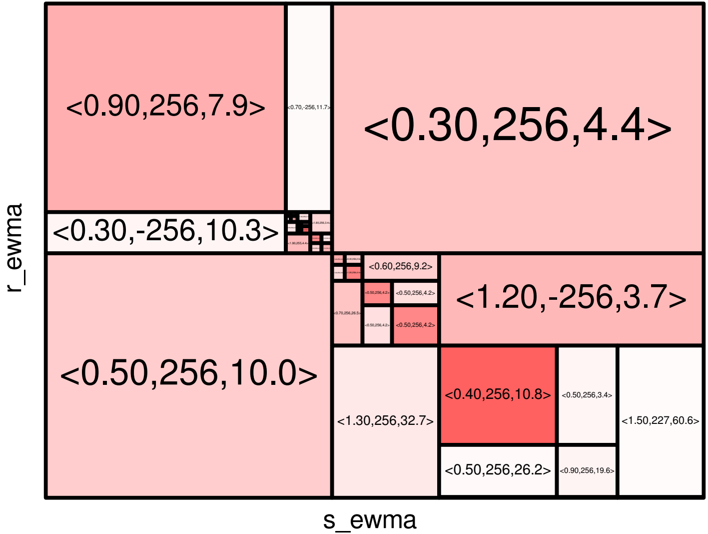
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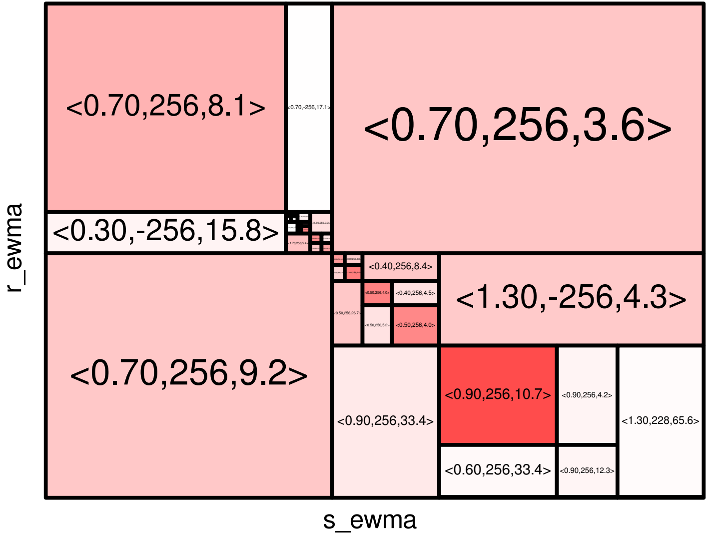

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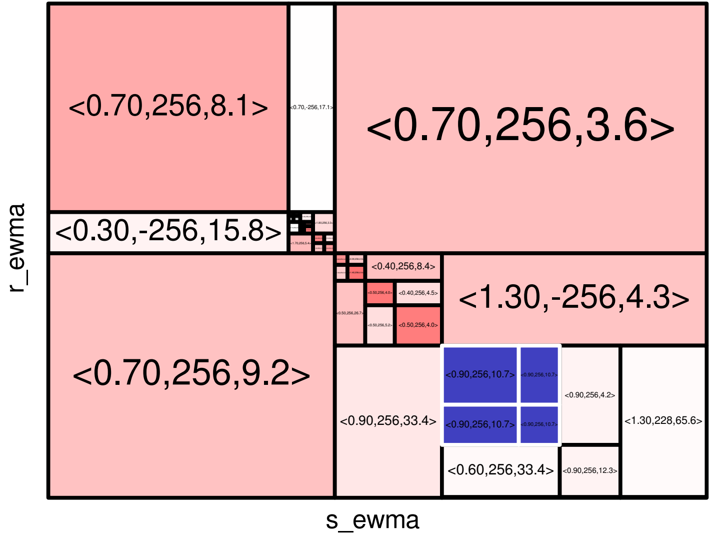

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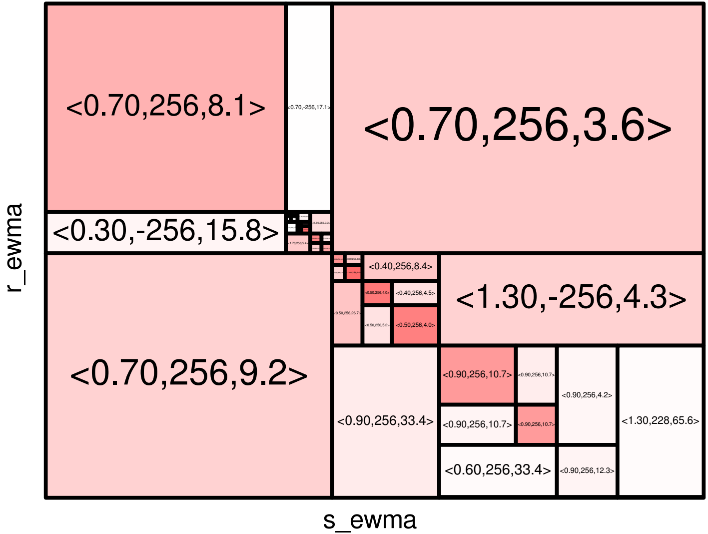
Optimize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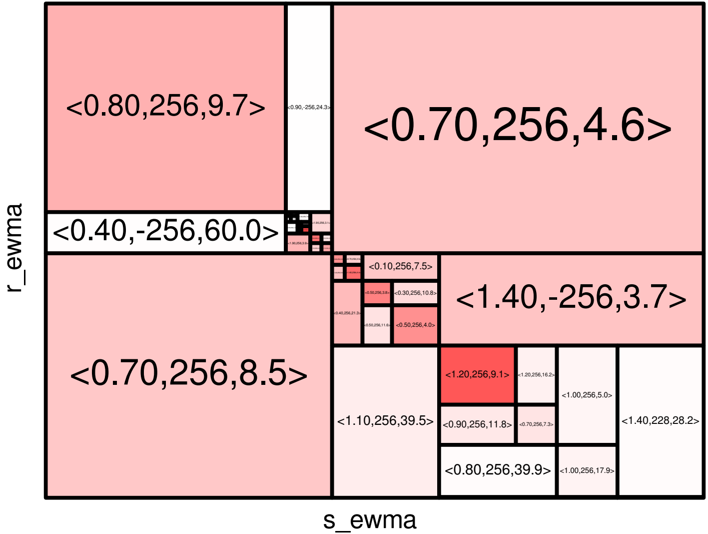
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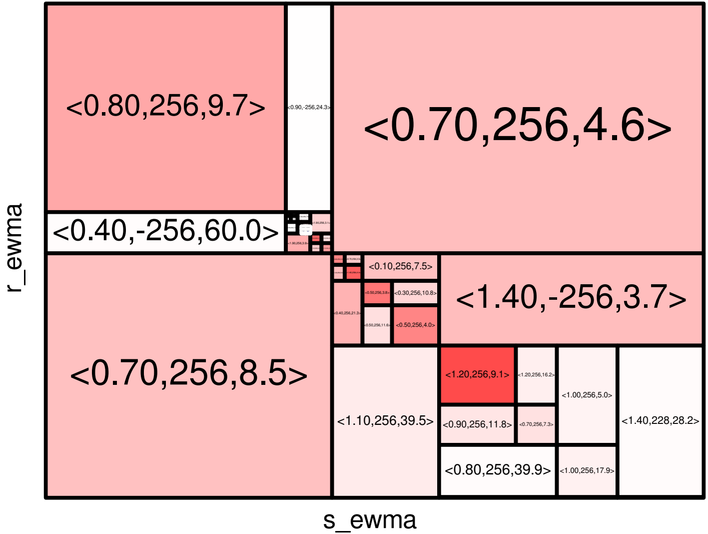

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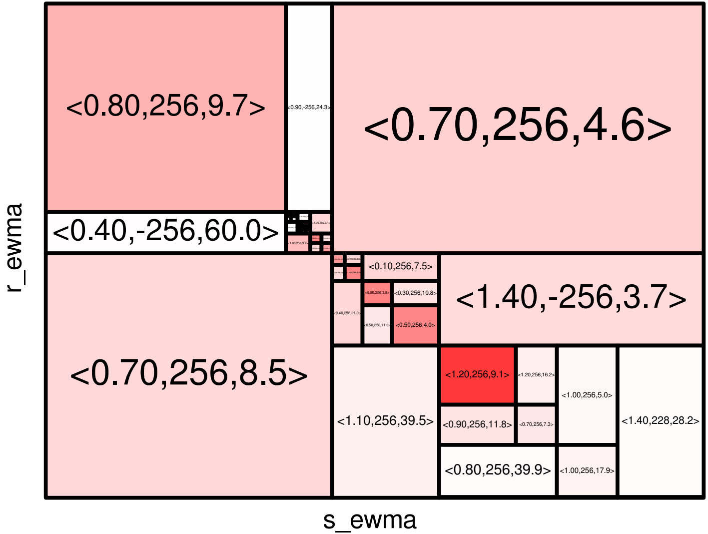

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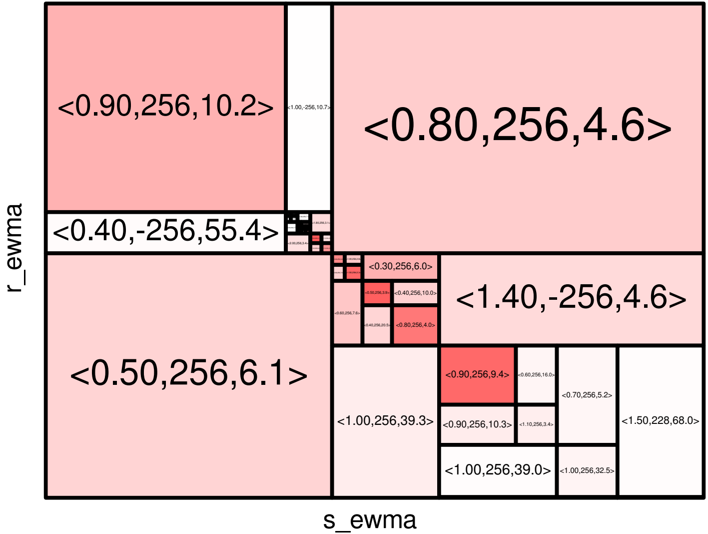
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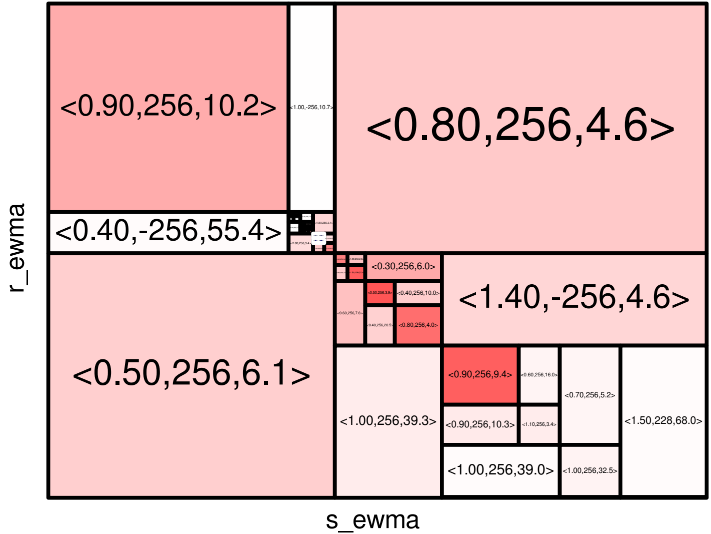
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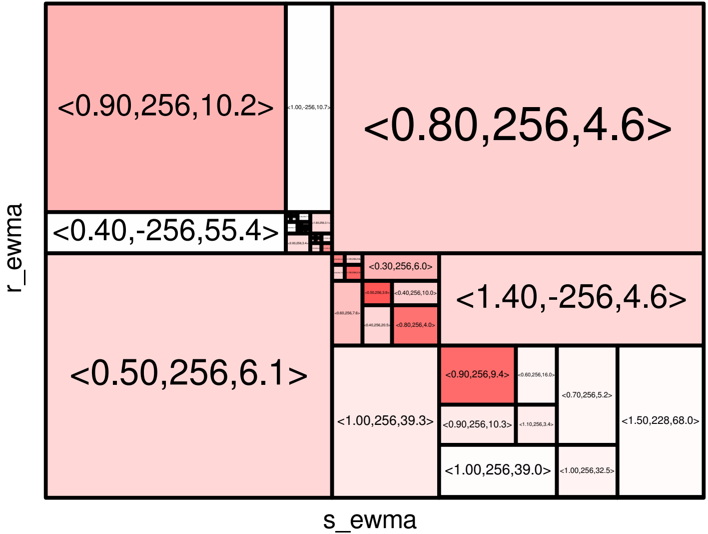
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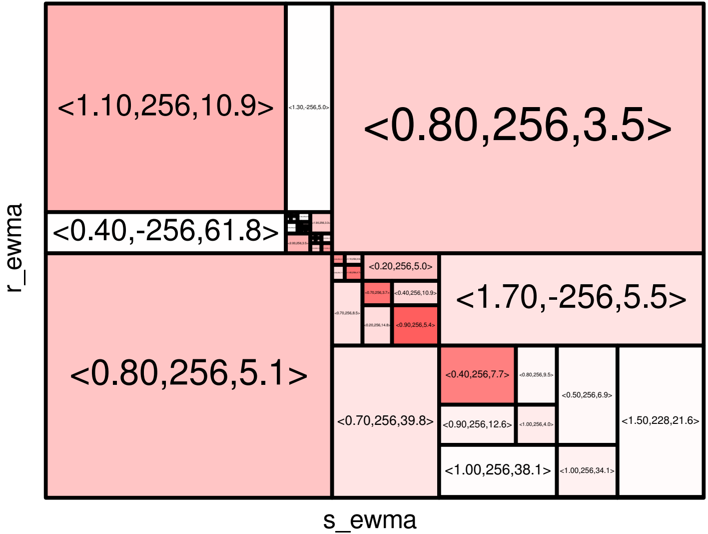
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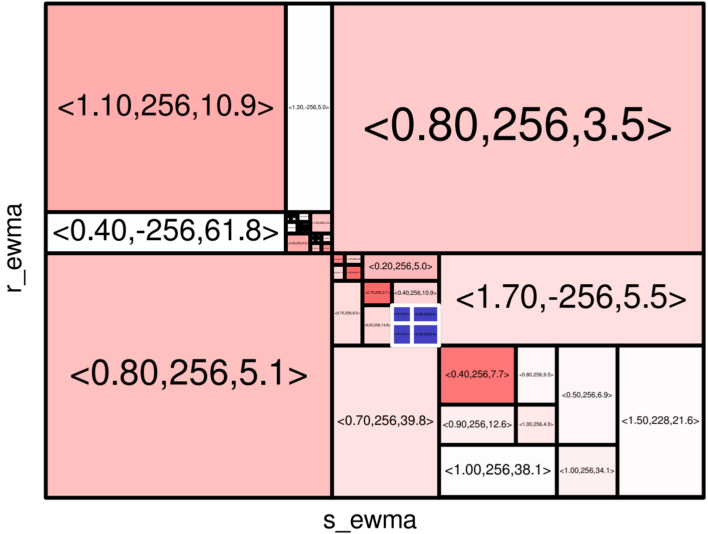
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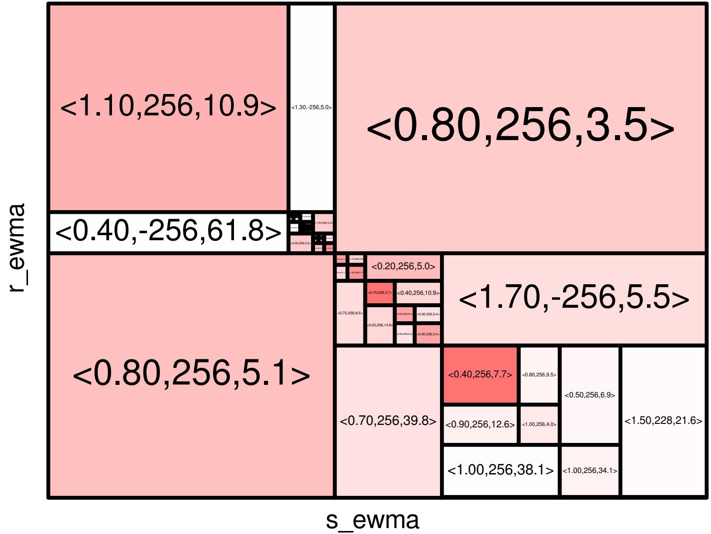

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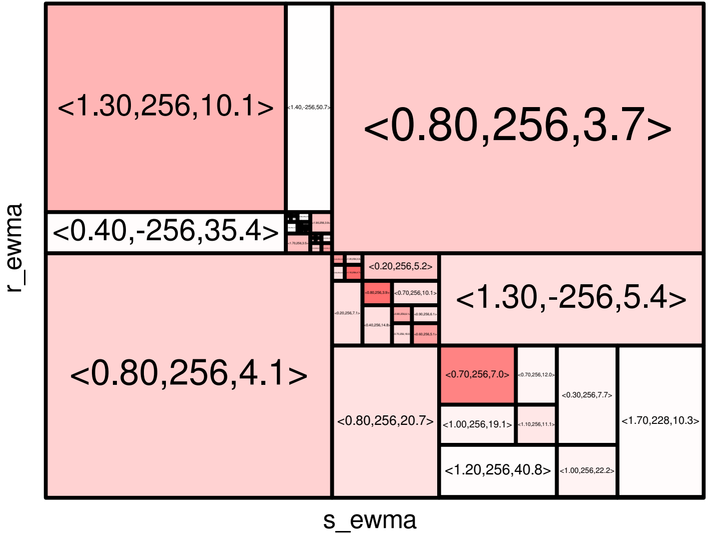
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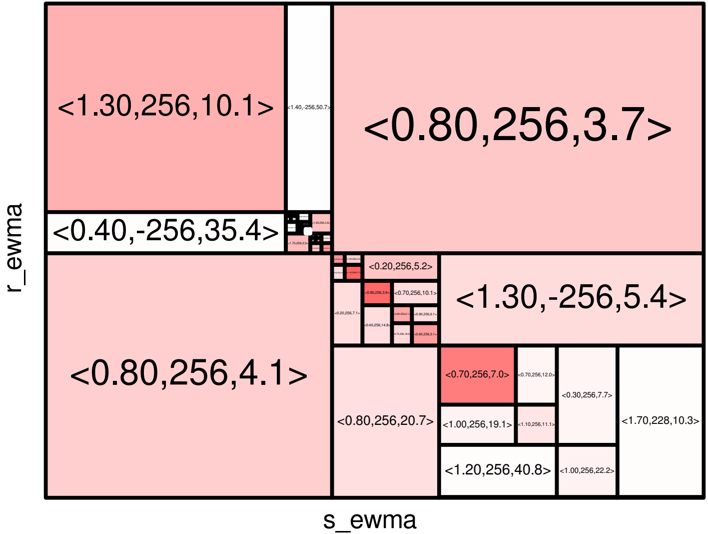

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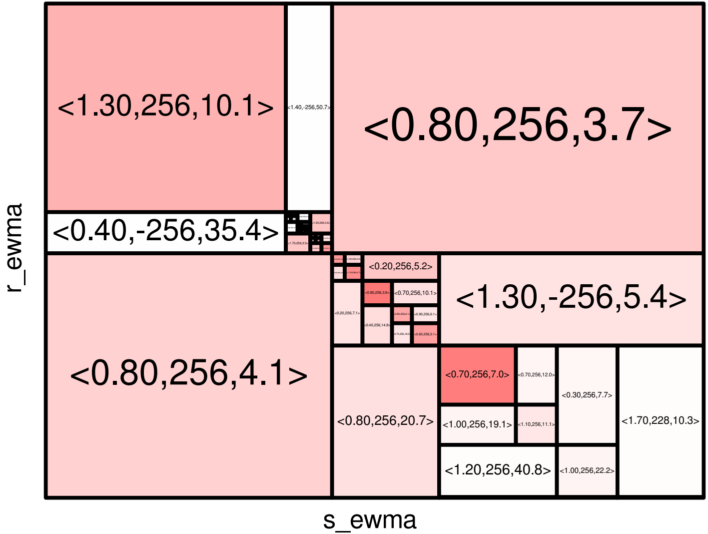
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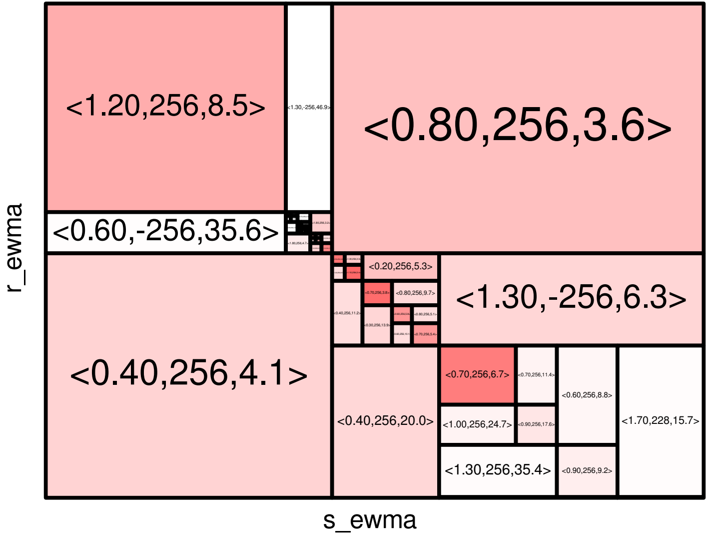
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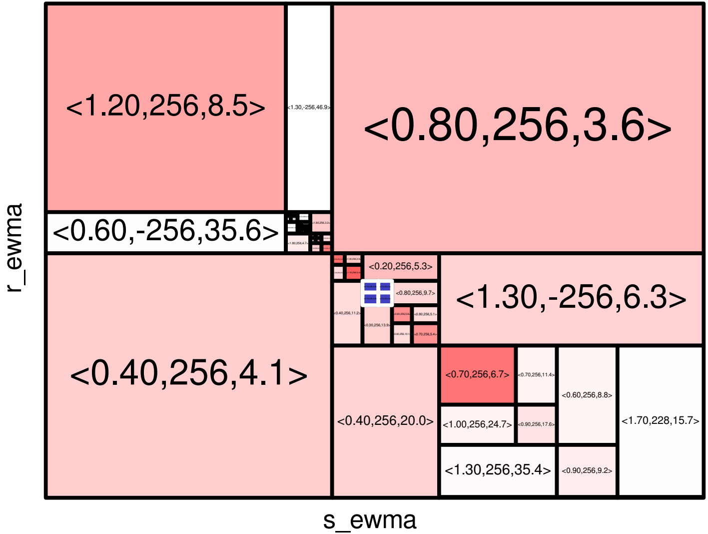
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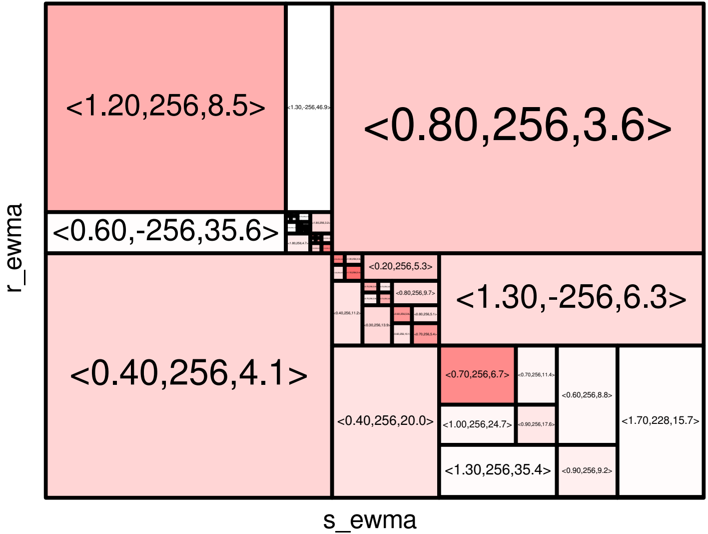
Optimize



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s_ewma

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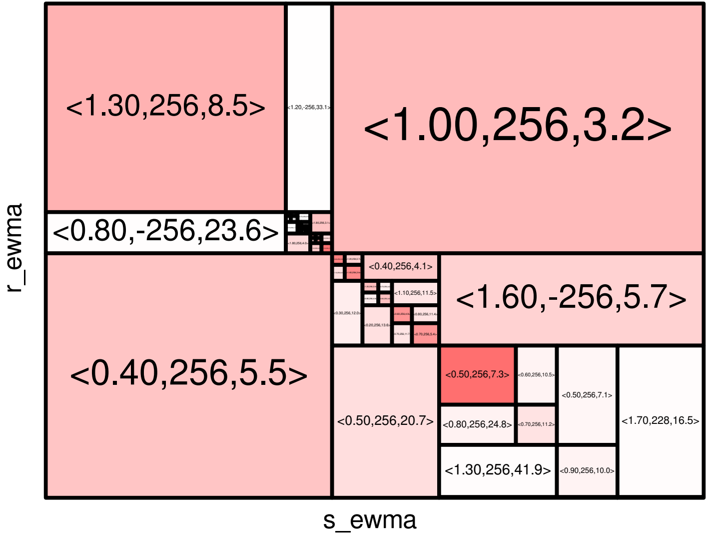
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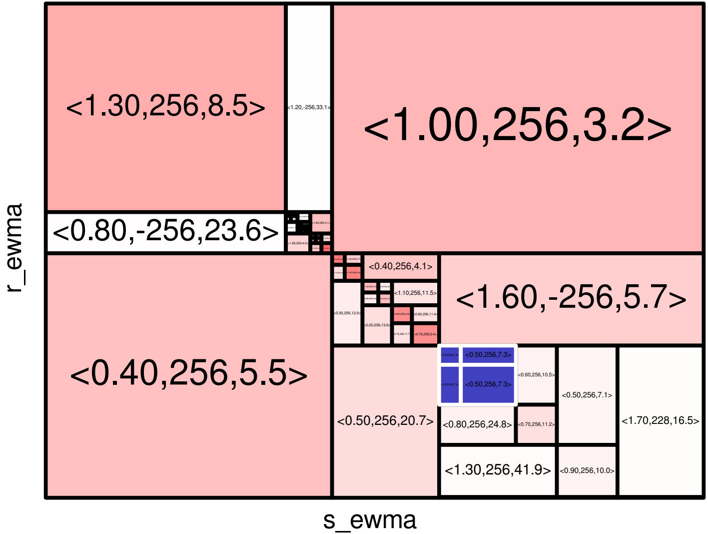
Simulate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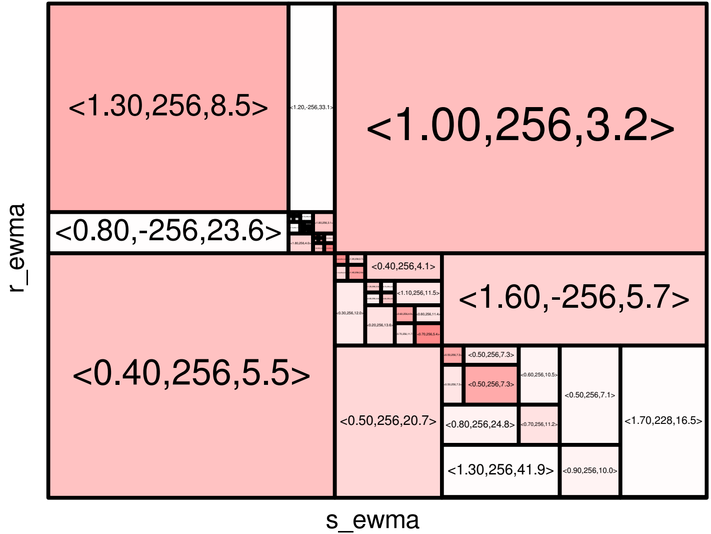
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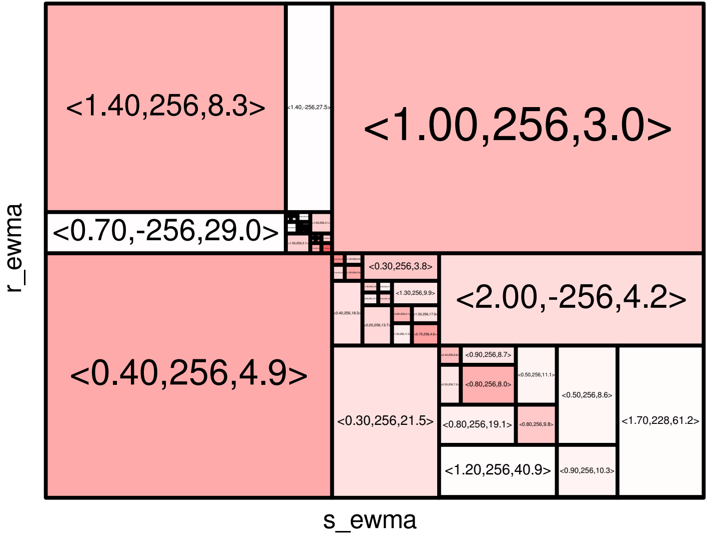
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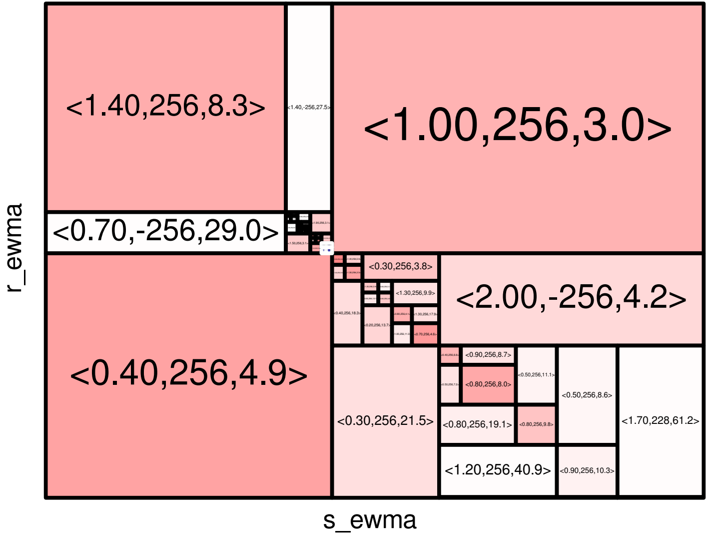
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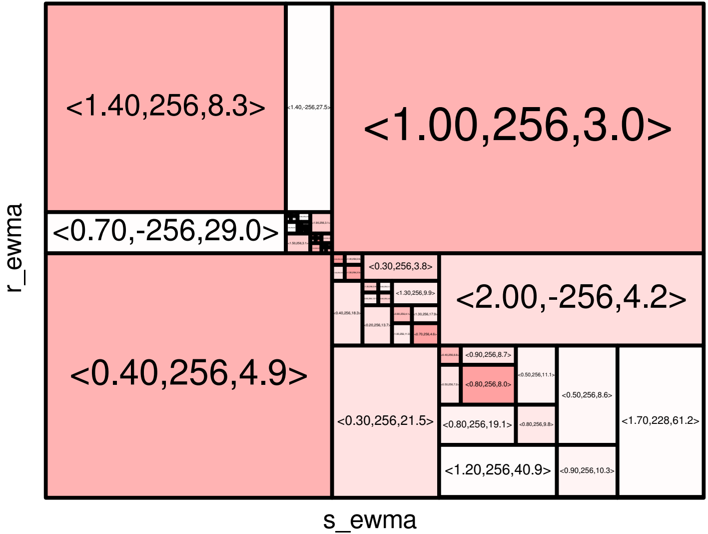
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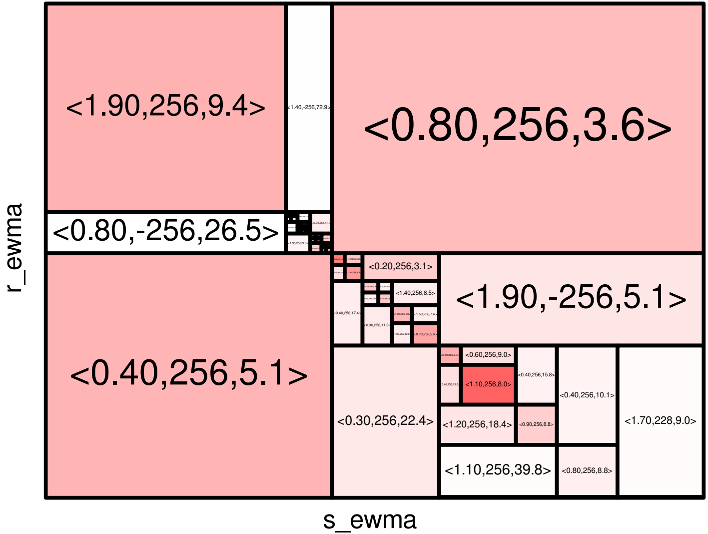
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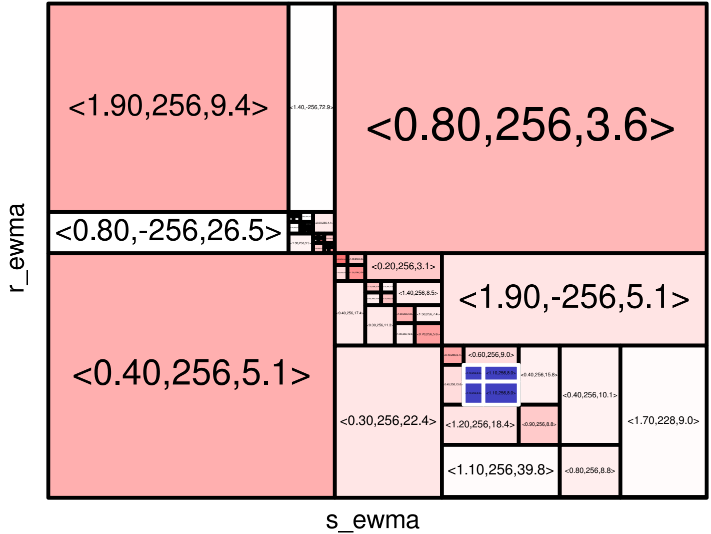
Simulate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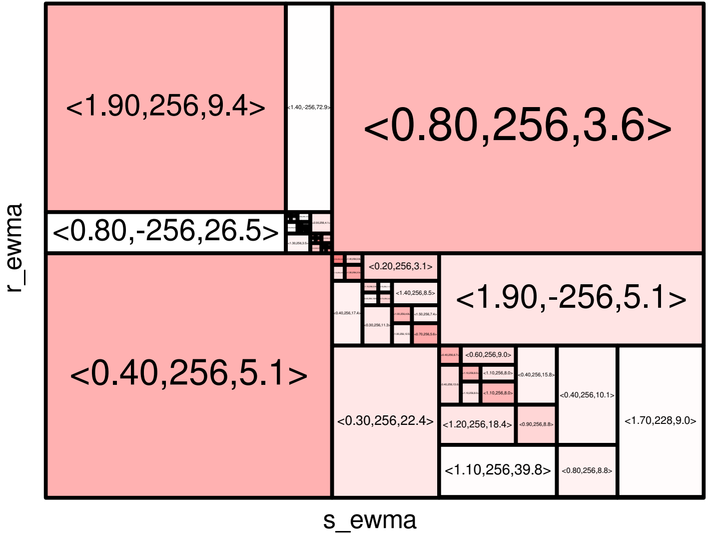
Optimize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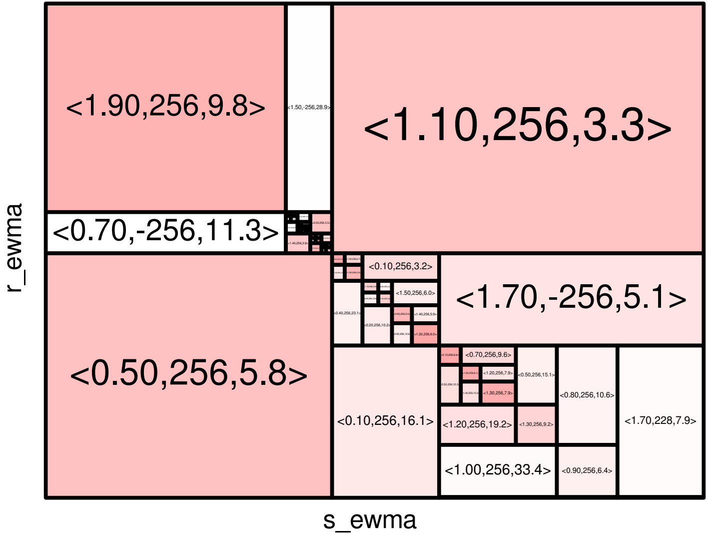

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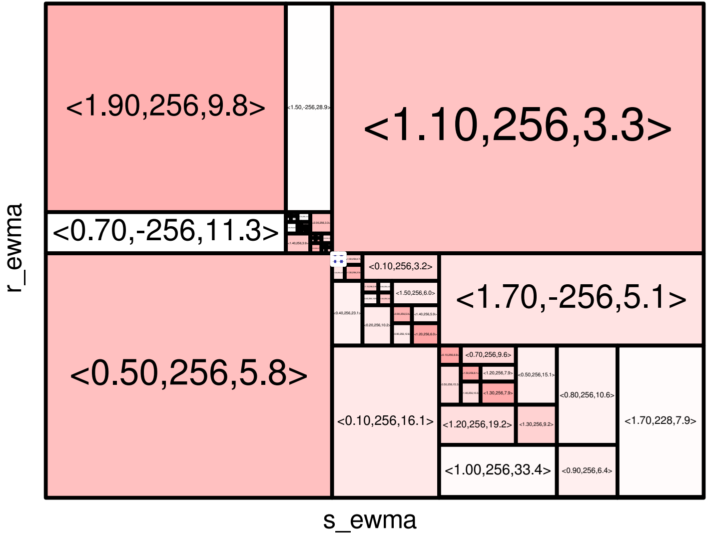
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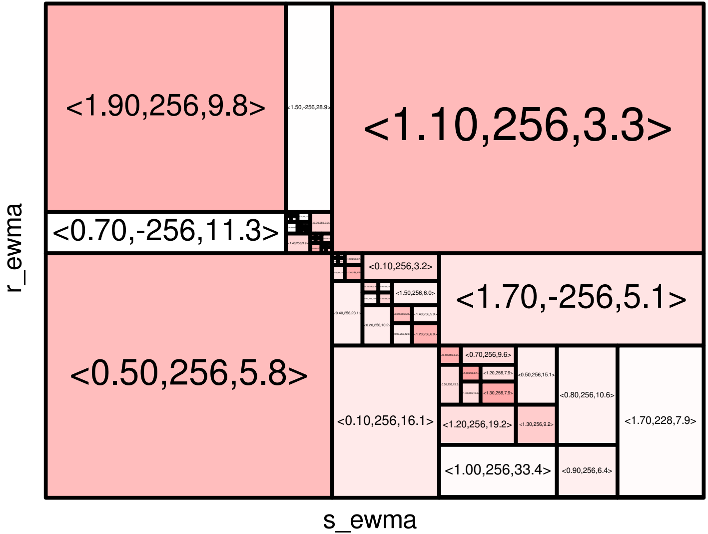
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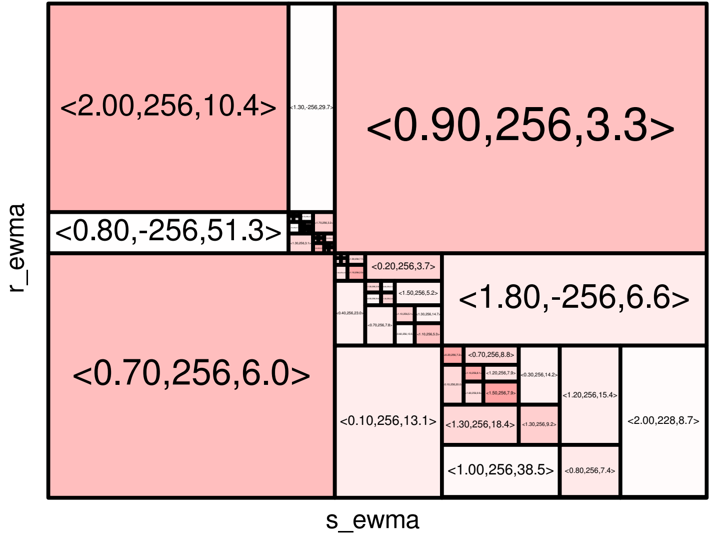

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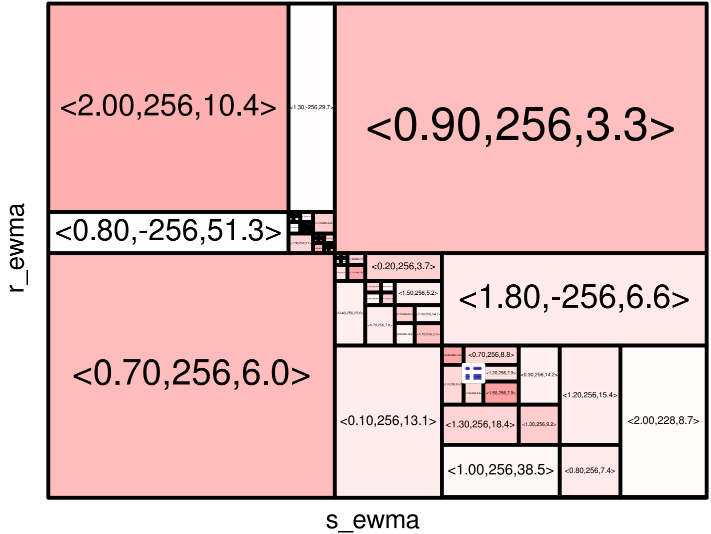
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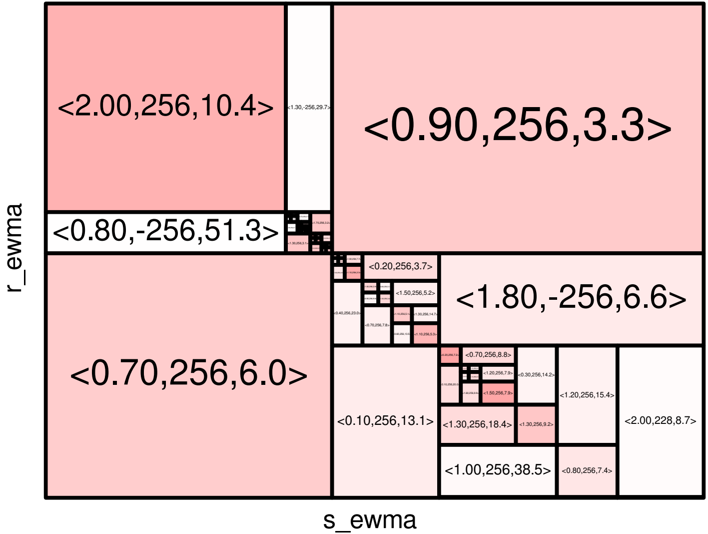
Optimize



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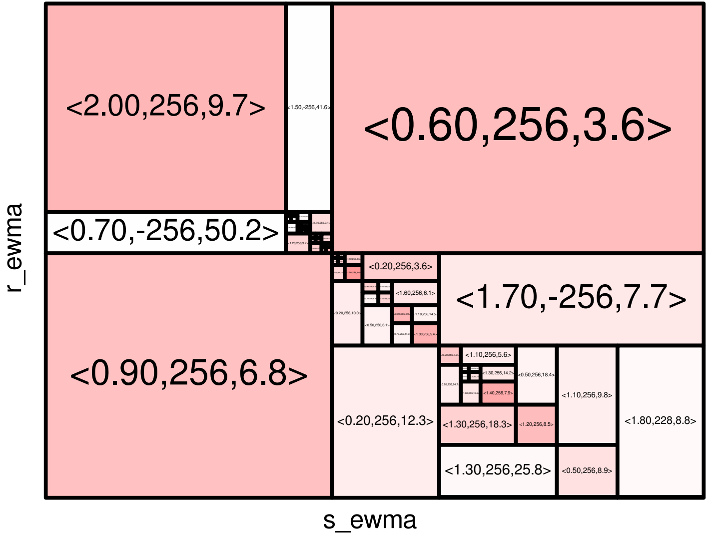
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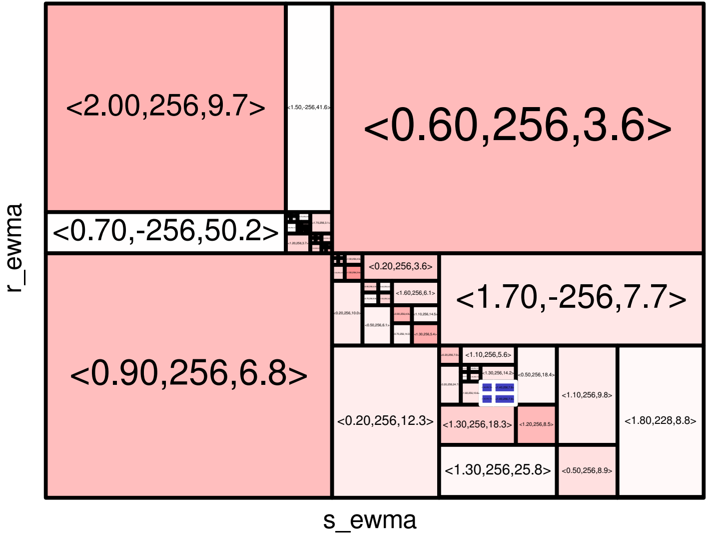
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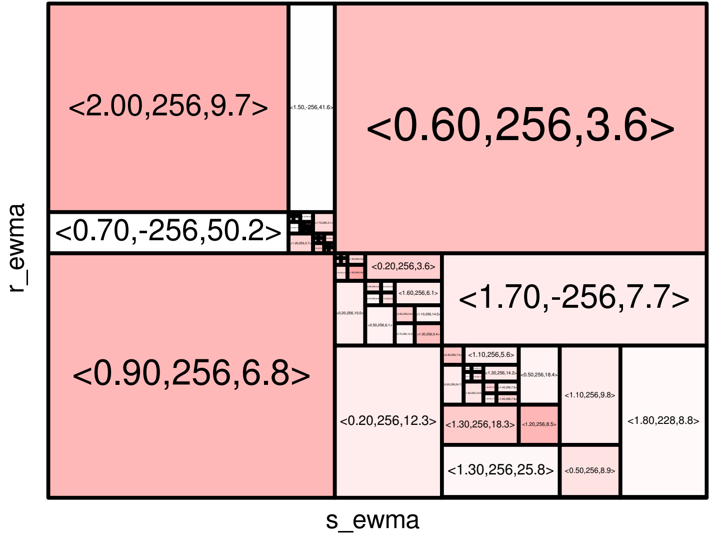

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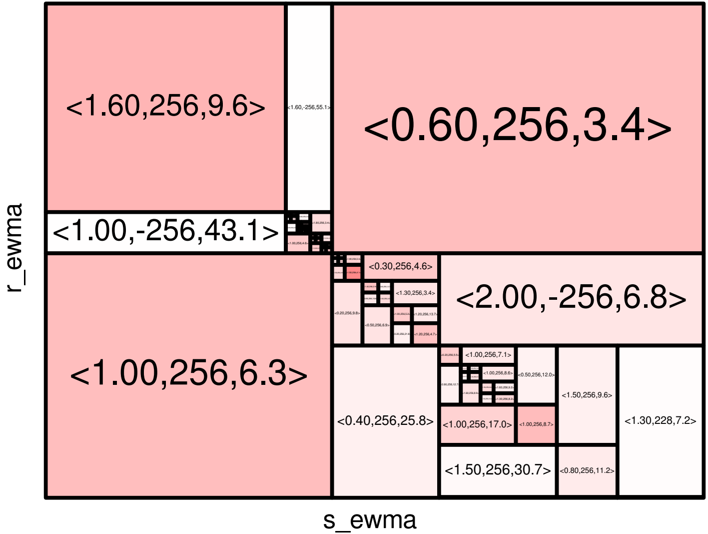
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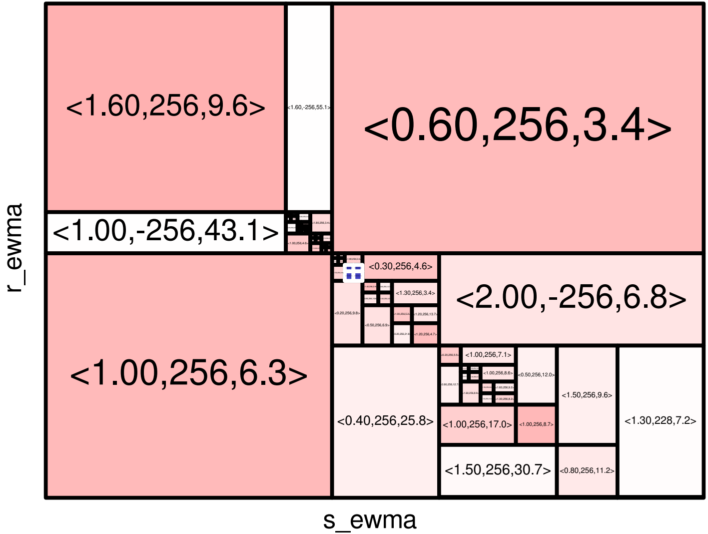
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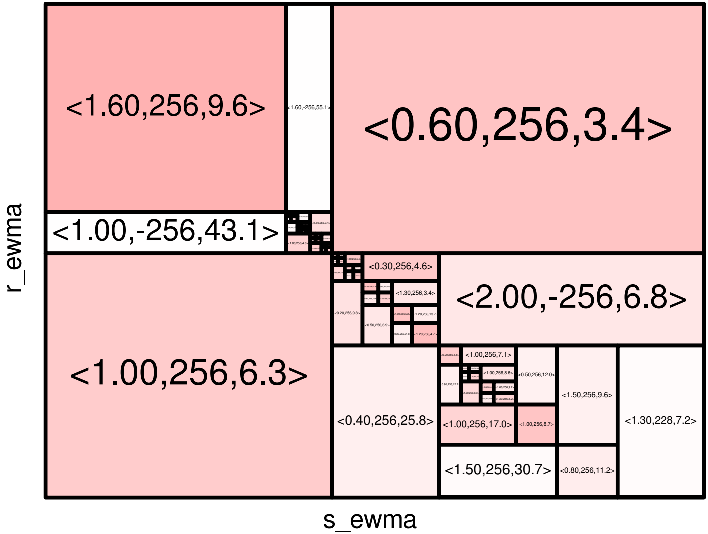
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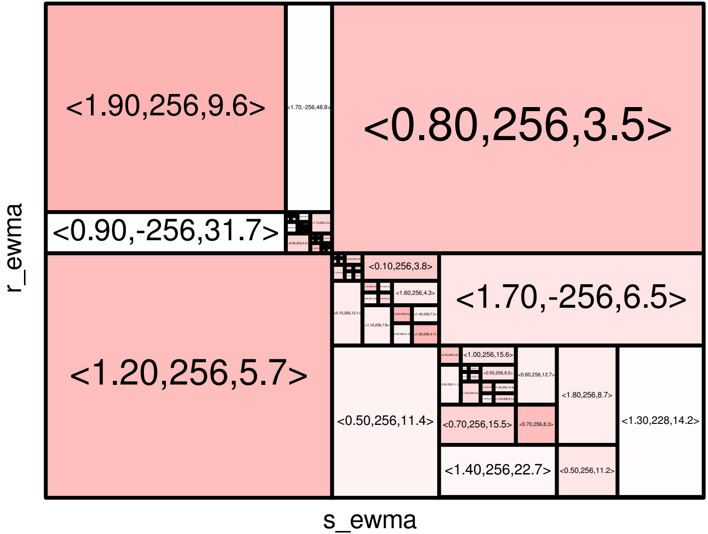
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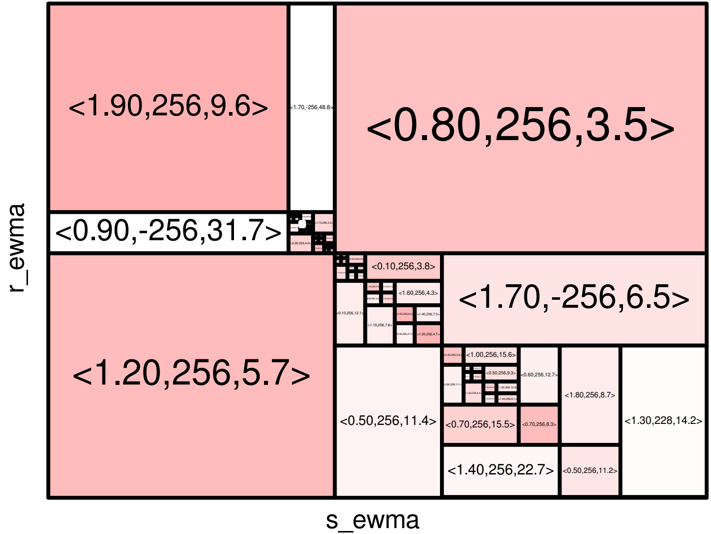
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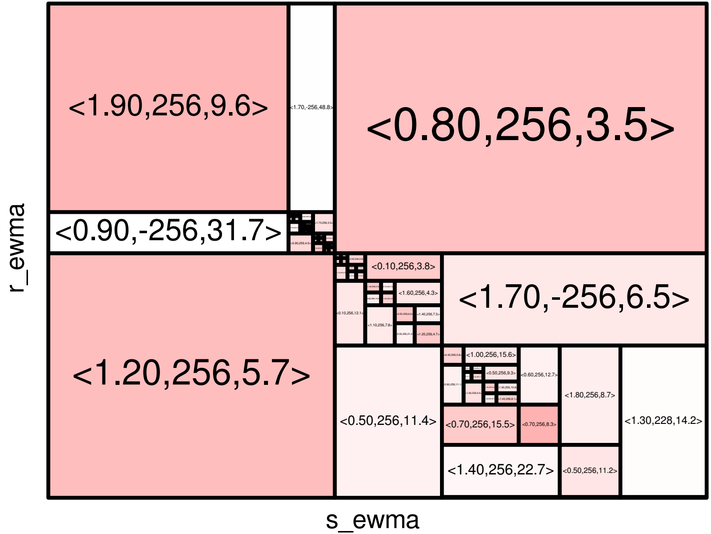
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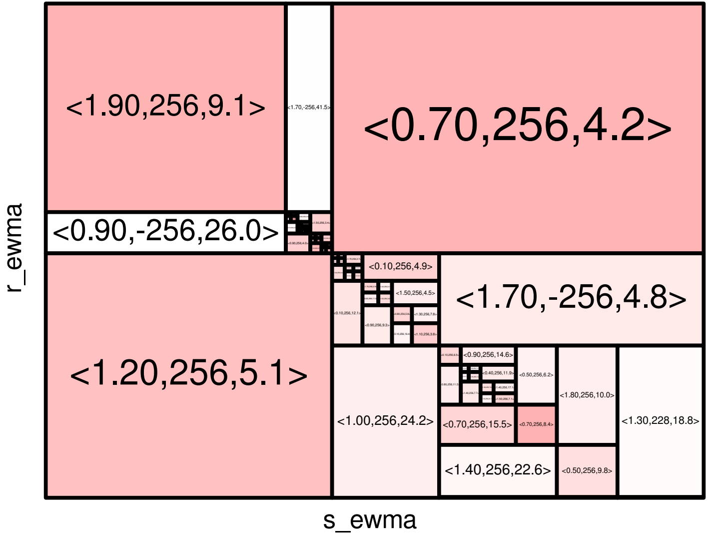
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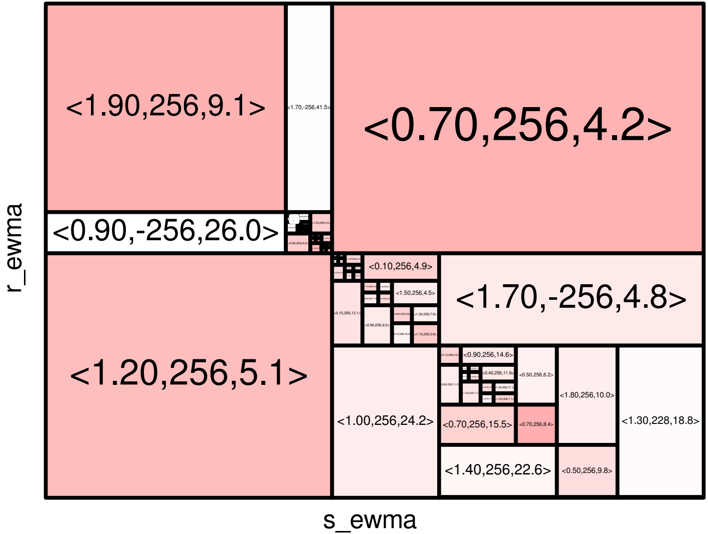
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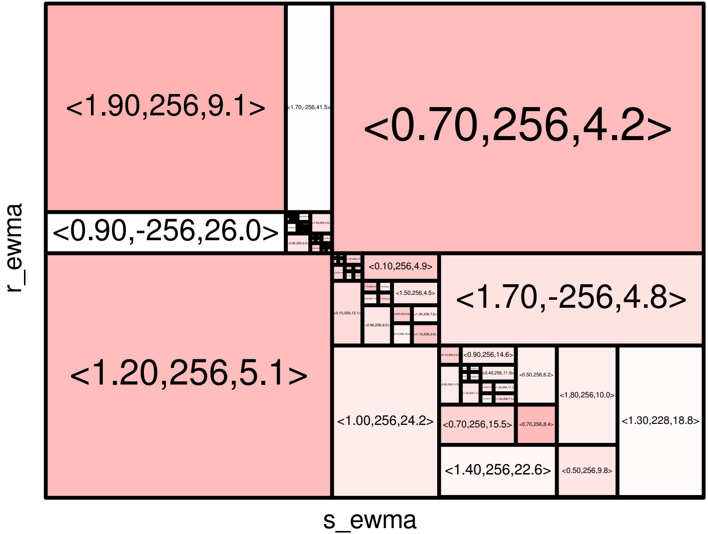
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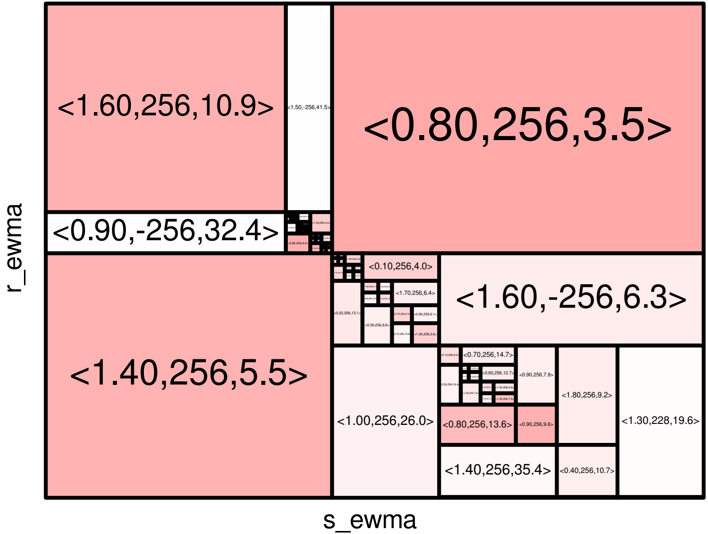
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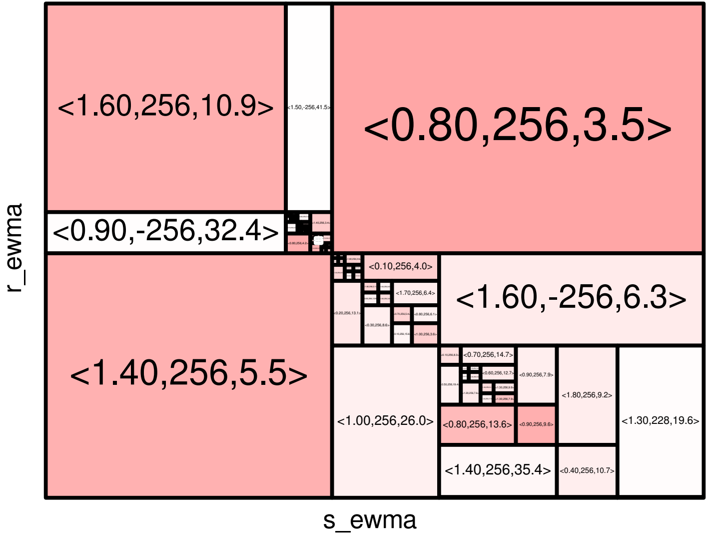
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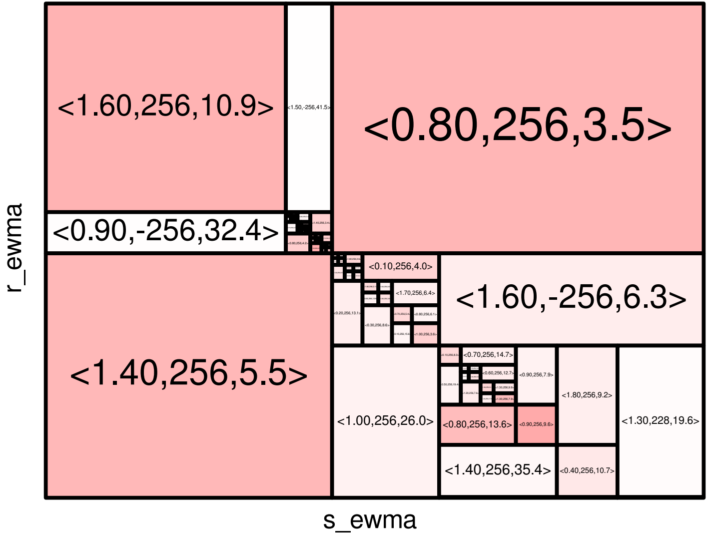
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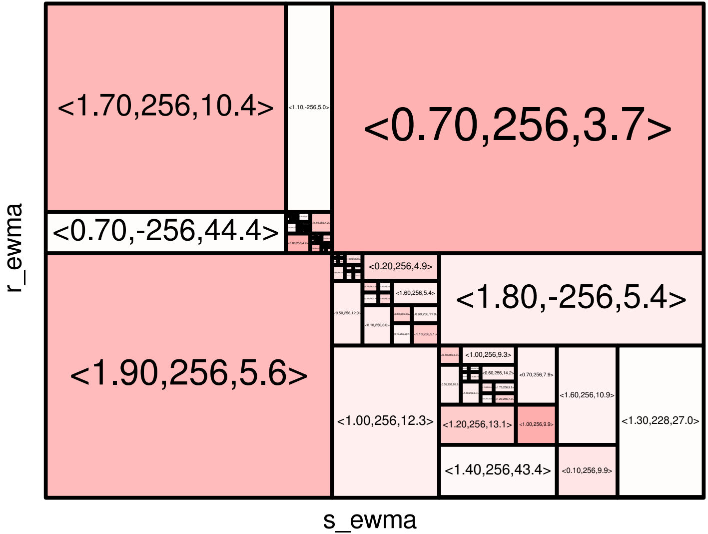
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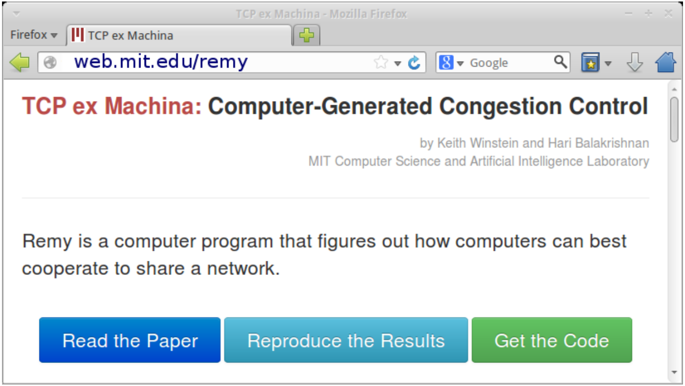
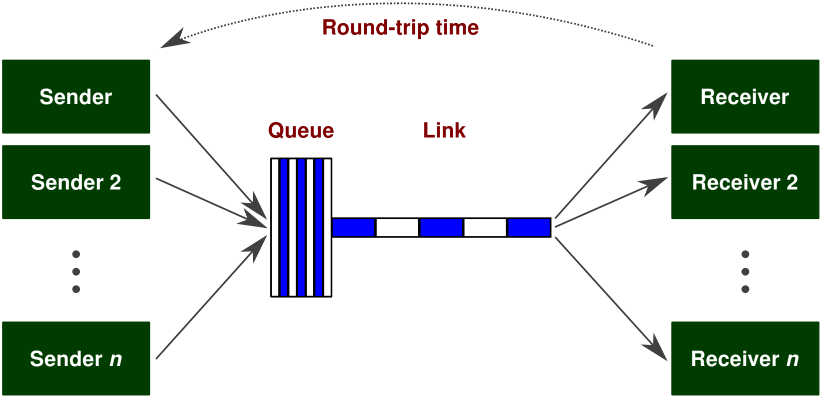
r_ewma
s_ewma

Evaluation in ns-2

- End-to-end comparators: NewReno, Cubic, Compound, Vegas
- In-net comparators: Cubic-over-sfqCoDel, XCP
- Simulation setup published for replication



Scenario 1: fixed-rate network, homogenous senders



Scenario 1: details

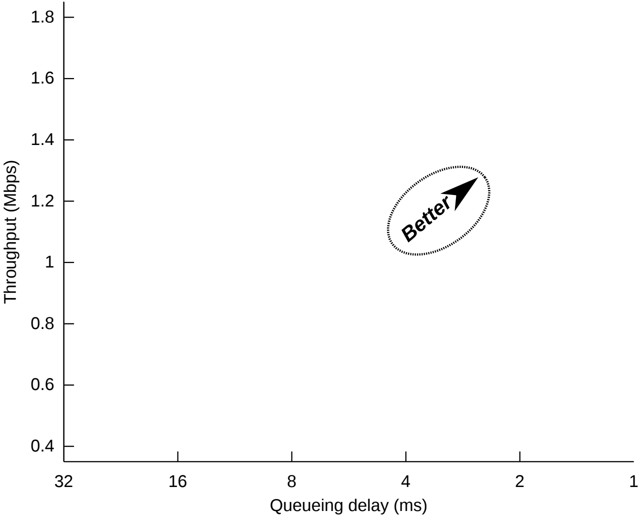
Quantity	Simulation parameter	Remy assumptions
Link speed	15 Mbps	Uniform(10, 20) Mbps
RTT	150 ms	Uniform(100, 200) ms
n	8	Uniform(1, 16)
"On" process	$\exp[\mu = 100]$ **kB**	$\exp[\mu = 5]$ **s**
"Off" process	$\exp\left[\mu = \frac{1}{2}\right]$ s	$\exp[\mu = \mathbf{5}]$ s

Remy objective:

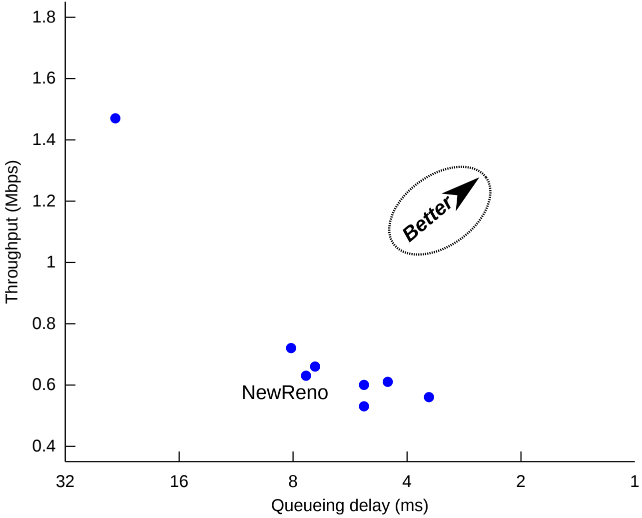
$$\sum_i \log \left[\frac{\text{throughput}_i}{(\text{delay}_i)^{\delta}} \right]$$

$$\delta \in \left\{ \frac{1}{10}, 1, 10 \right\}$$

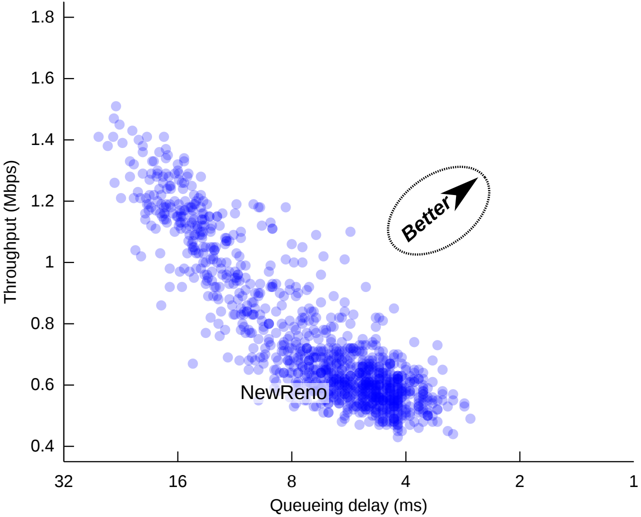
Scenario 1: throughput-delay plot



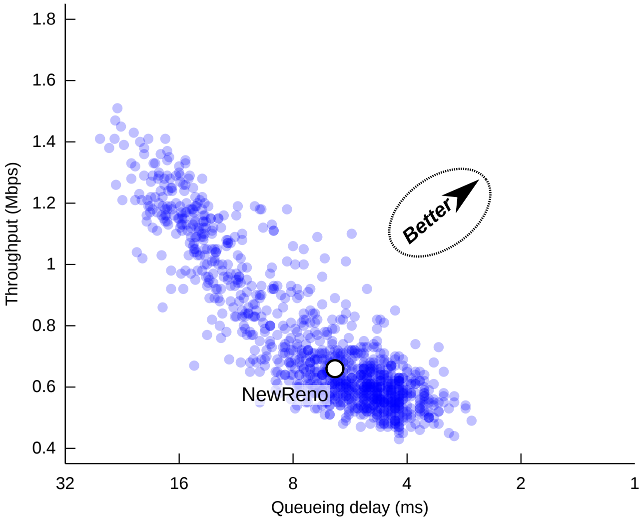
Scenario 1: throughput-delay plot



Scenario 1: throughput-delay plot



Scenario 1: throughput-delay plot



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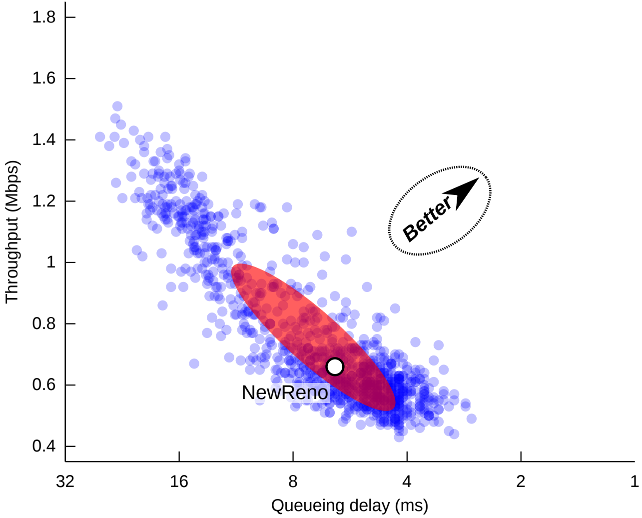

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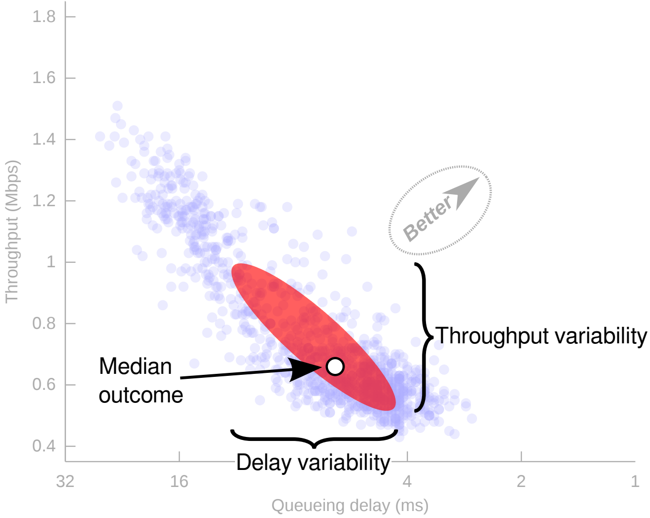

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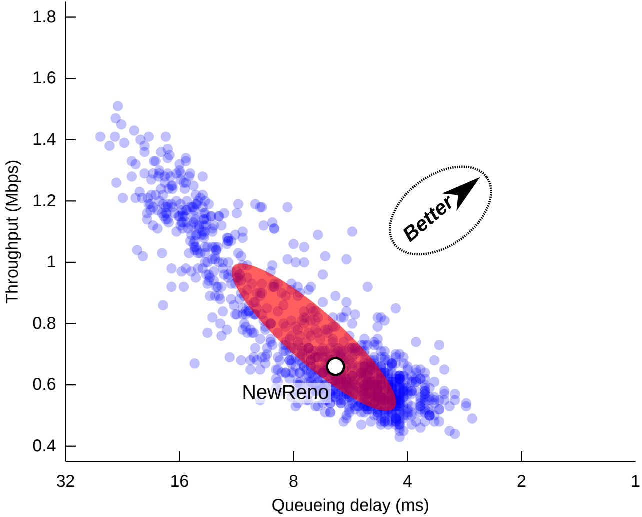

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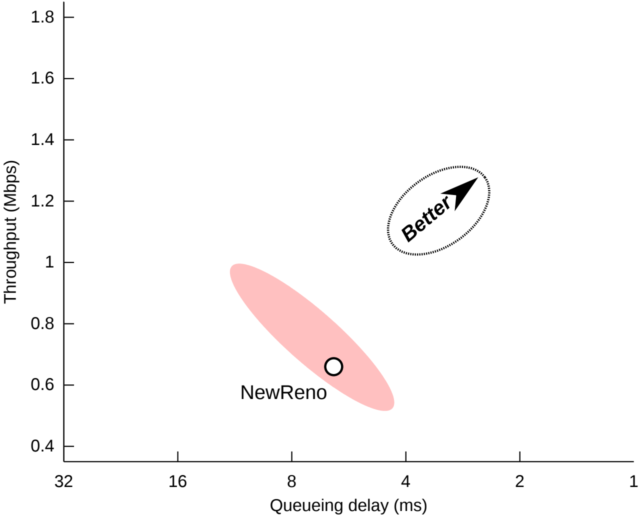

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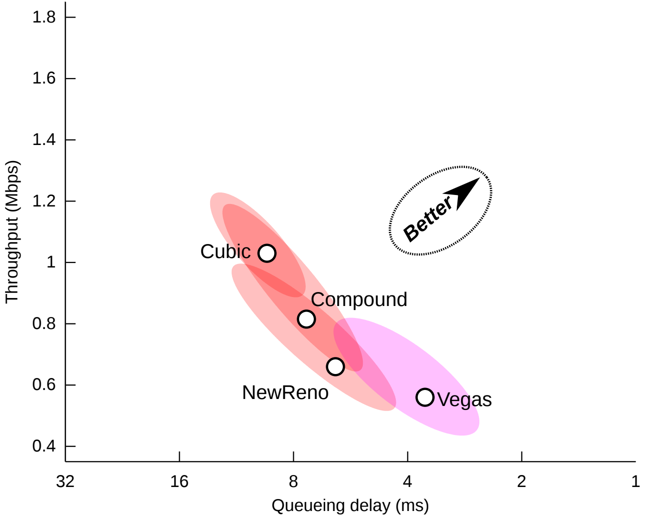

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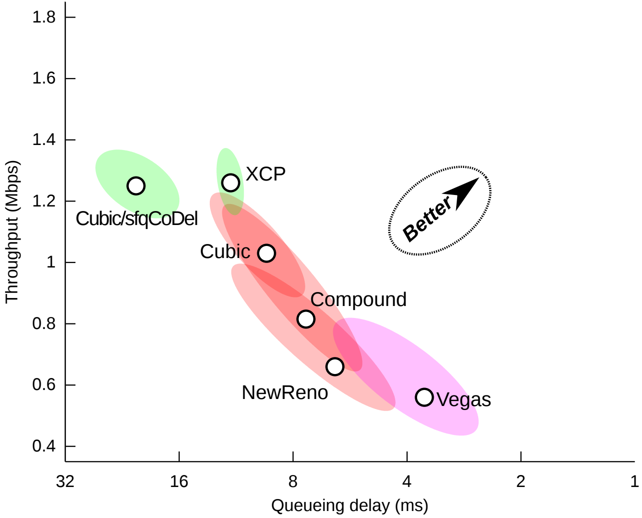
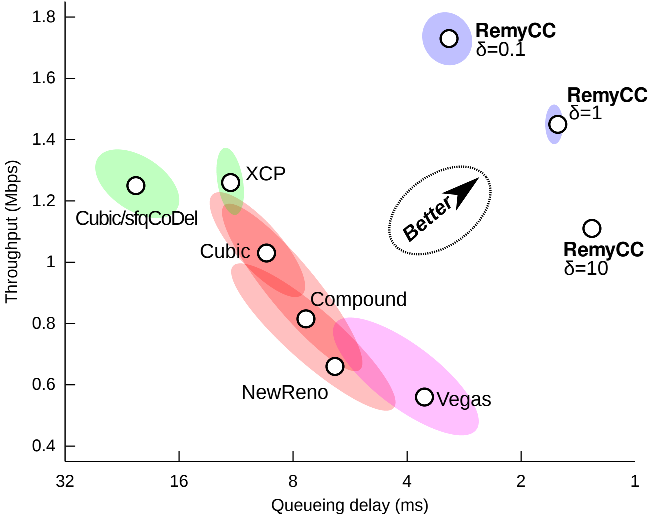


Scenario 1: throughput-delay plot



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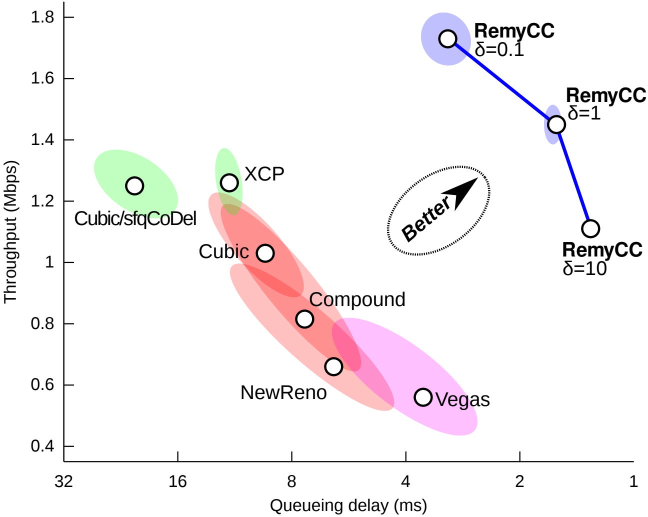
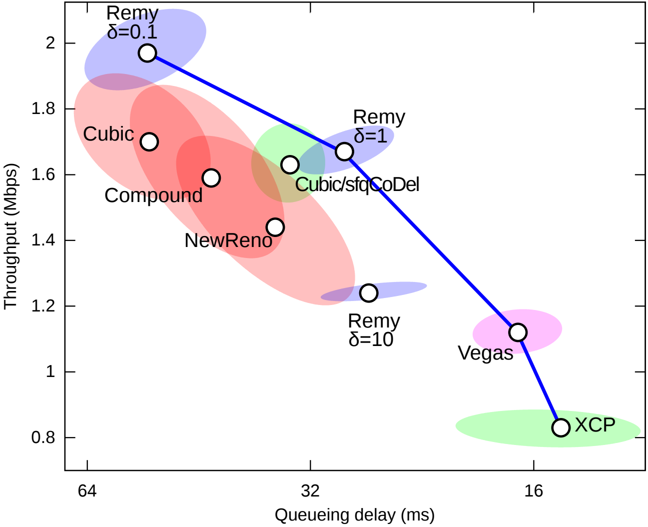


Scenario 2: Verizon LTE, $n = 8$

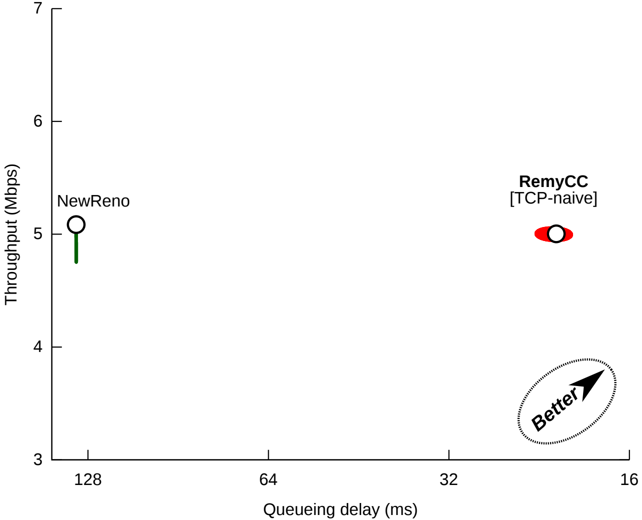


Remy as an instrument to study network science

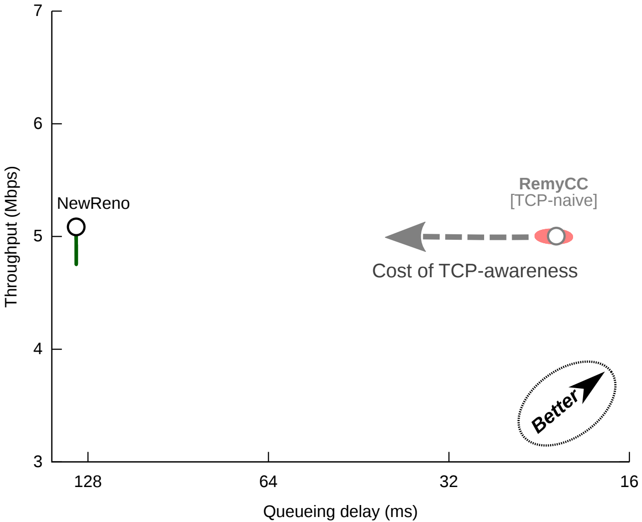
From the perspective of an endpoint, **what does it help to know** *about the network?*

How difficult is it to learn a good protocol, given an **imperfect** *model of the network?*

RemyCC competing against itself



RemyCC competing against itself



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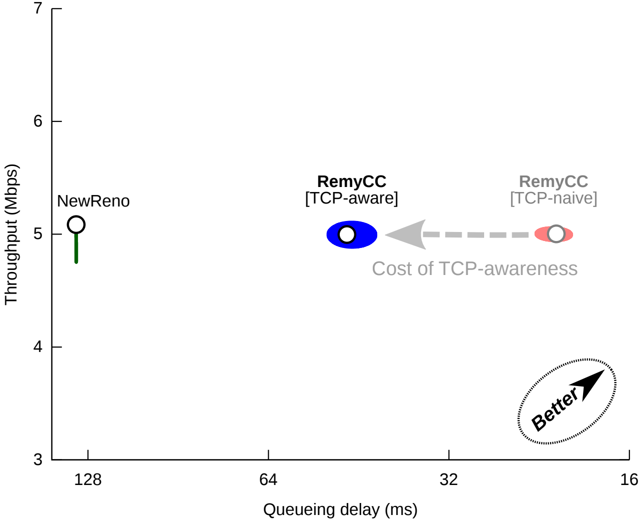
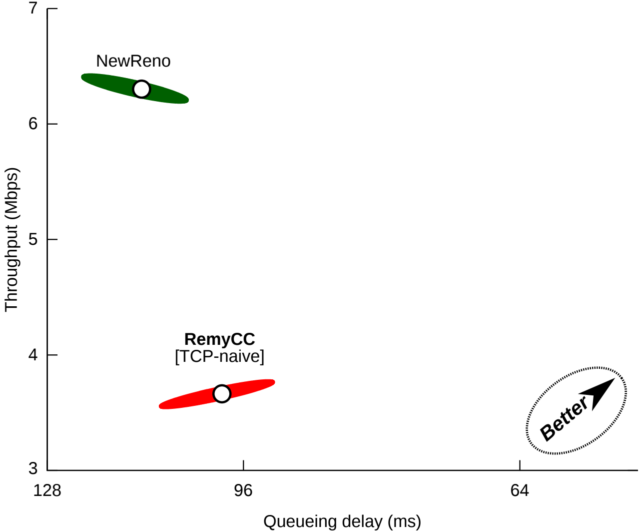
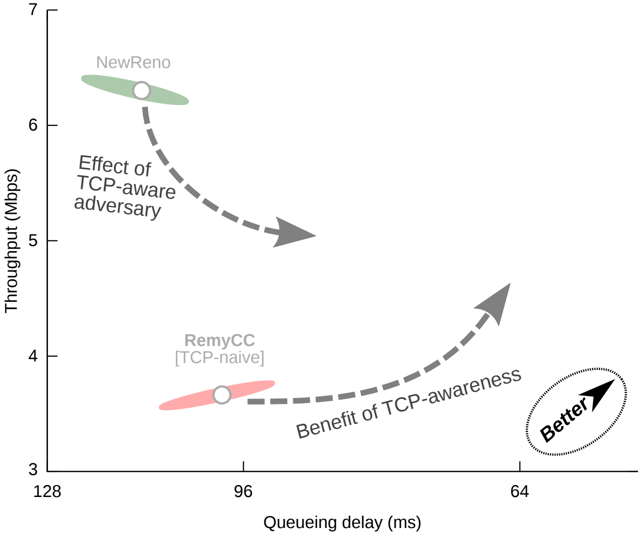


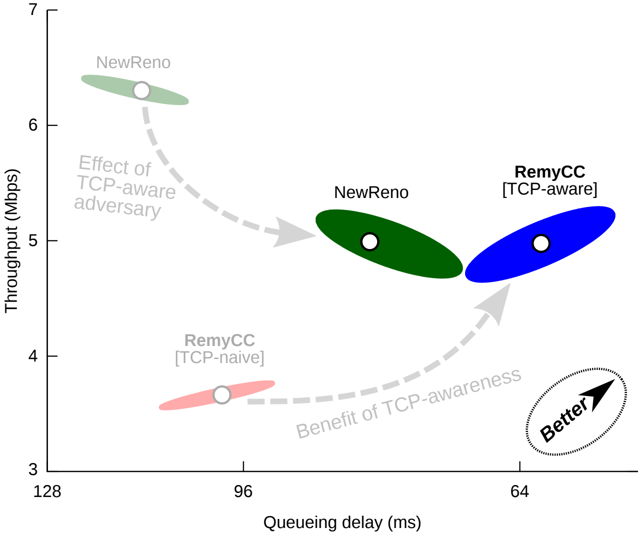
RemyCC competing against TCP NewReno



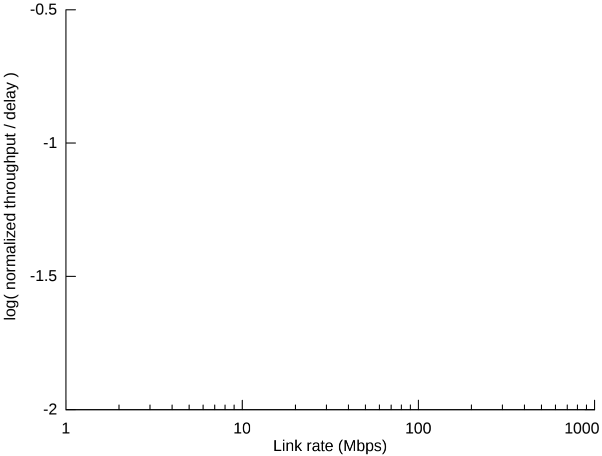
RemyCC competing against TCP NewReno



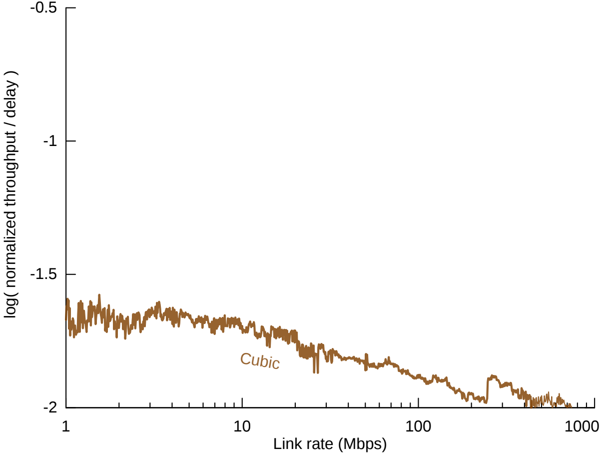
RemyCC competing against TCP NewReno



The cost of generality



The cost of generality



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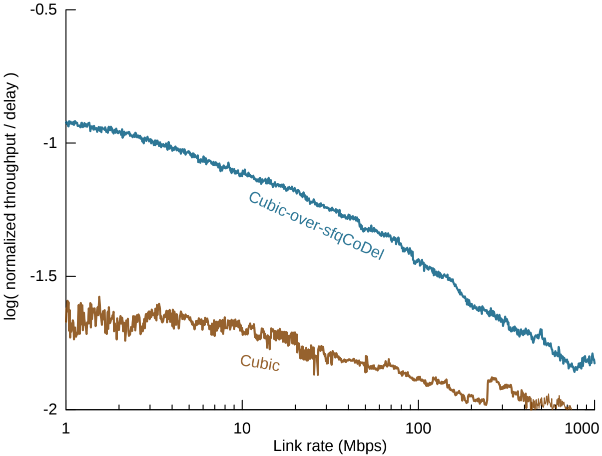

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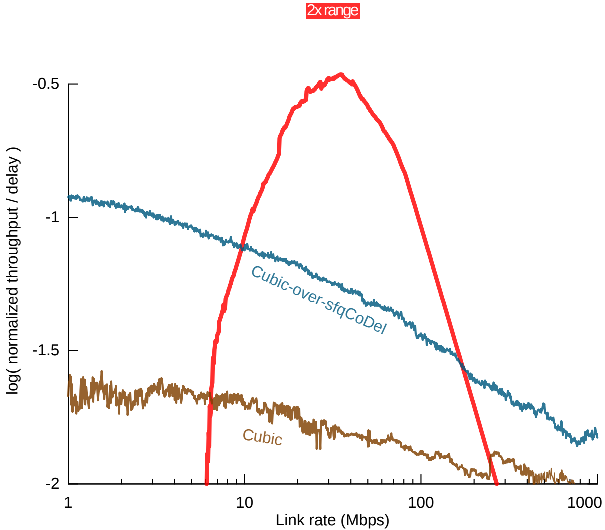

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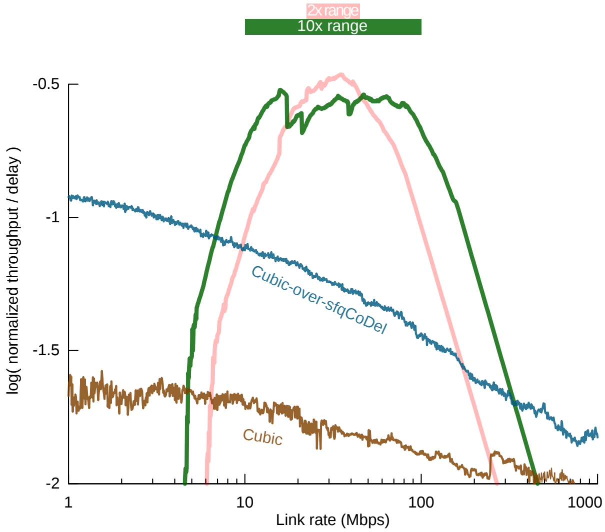

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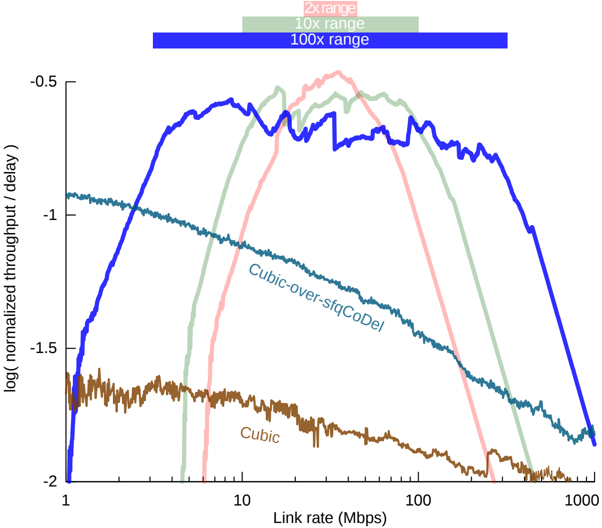
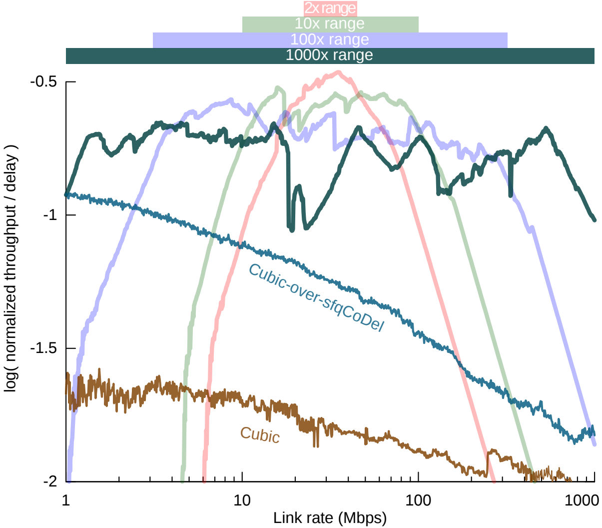


The cost of generality



Systems ex Machina

- Explicit design considerations → **freedom to make changes**
- "If this system is the answer, what's the question?"

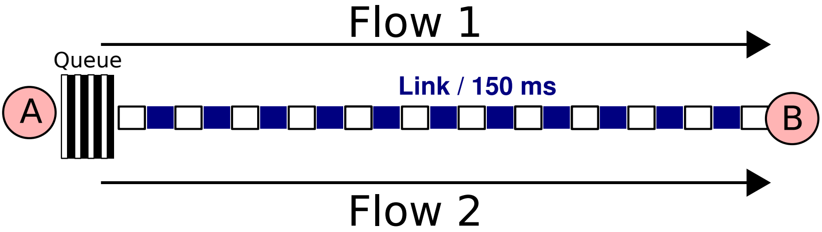
Sprout 2–4× the throughput and 7–9× less delay than Skype, etc.
Remy computer-generated protocol design

keithw@mit.edu

http://mit.edu/keithw

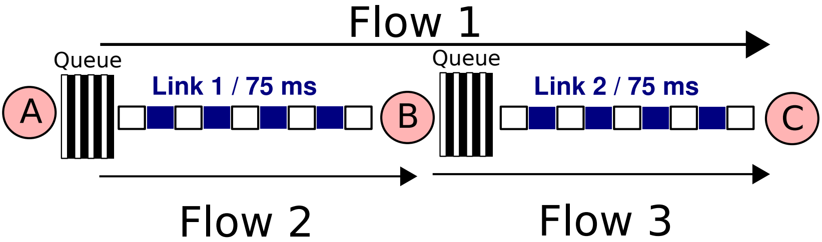
When the model is wrong about the topology

One bottleneck

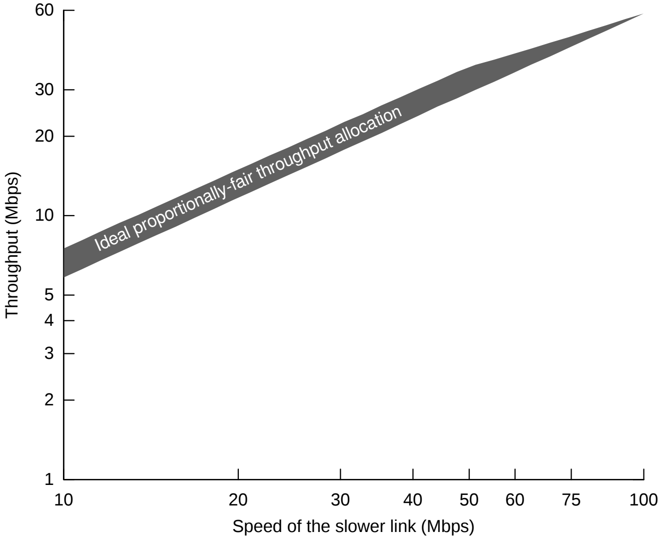


When the model is wrong about the topology

Two bottlenecks



When the model is wrong about the topology



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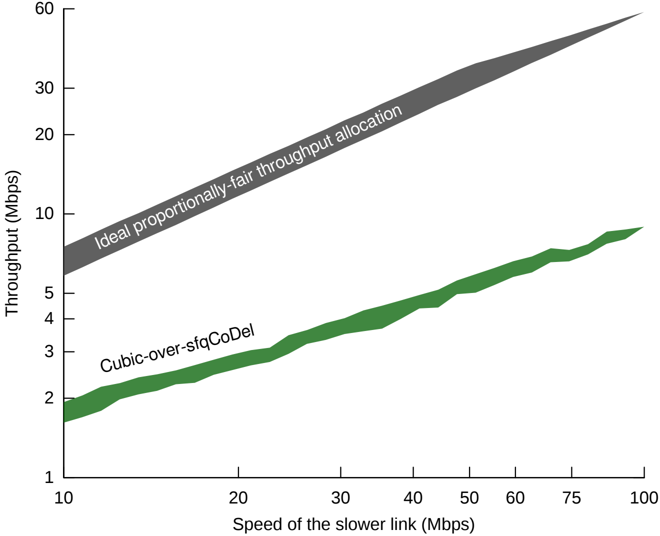

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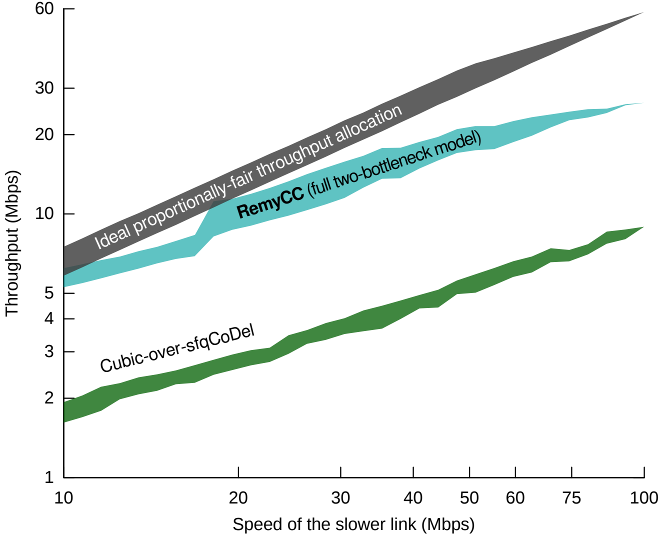
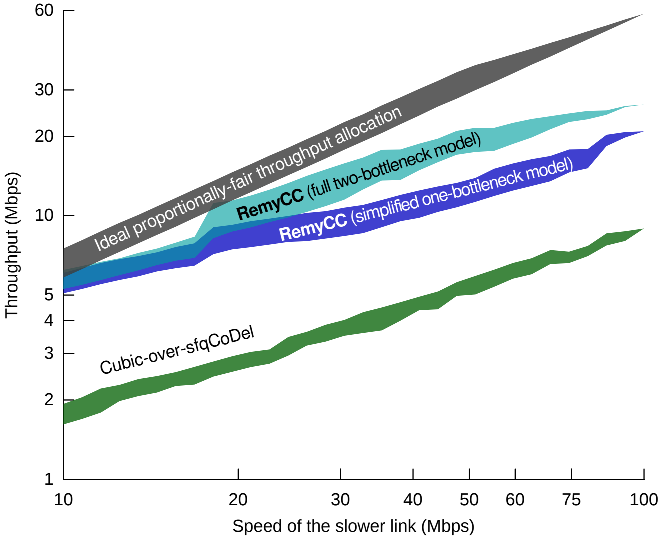
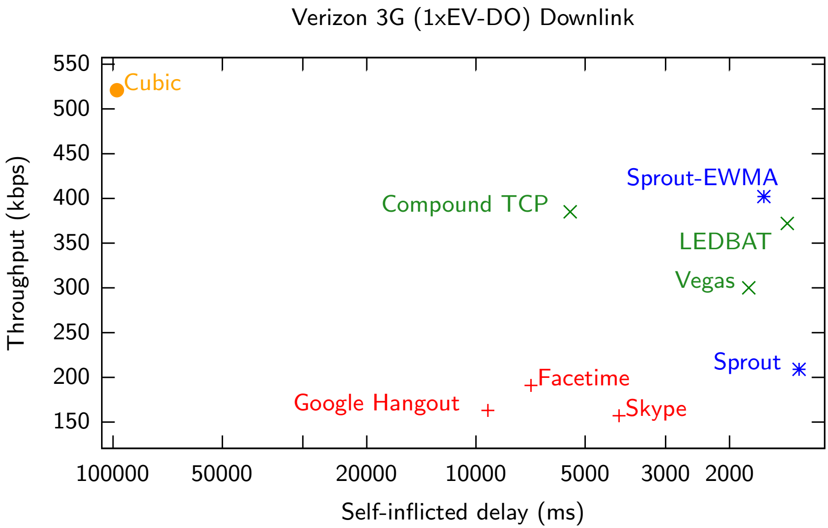
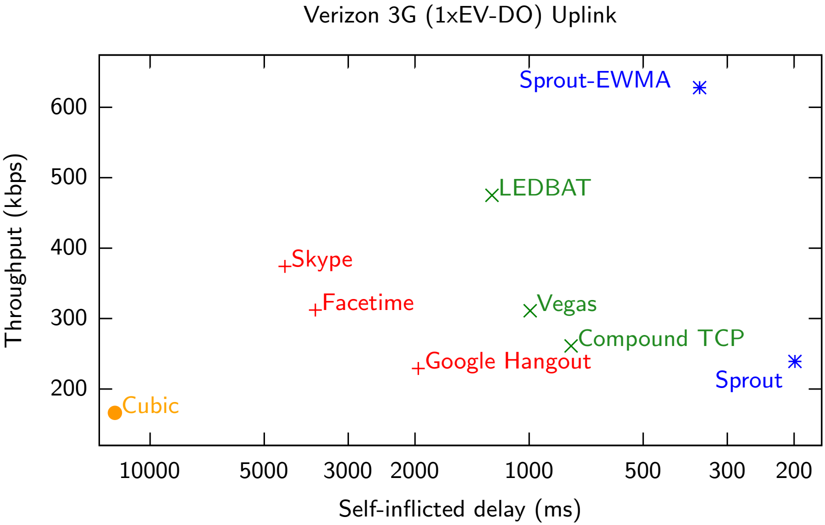
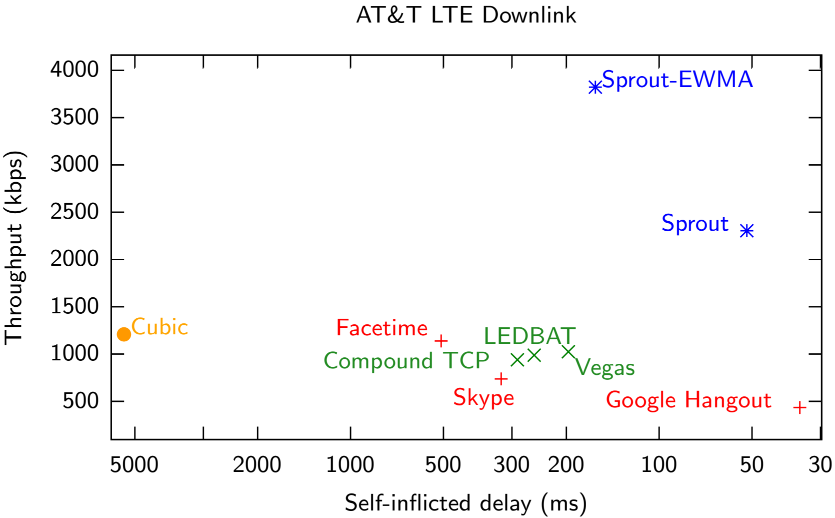


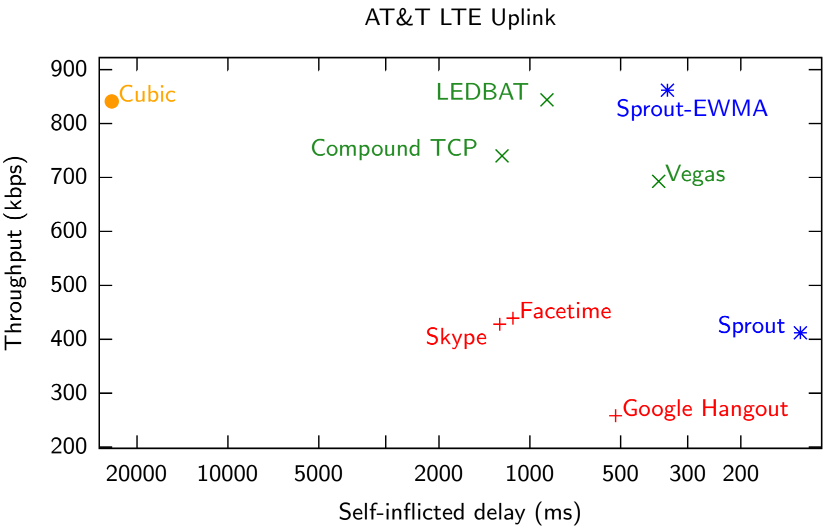
When the model is wrong about the topology

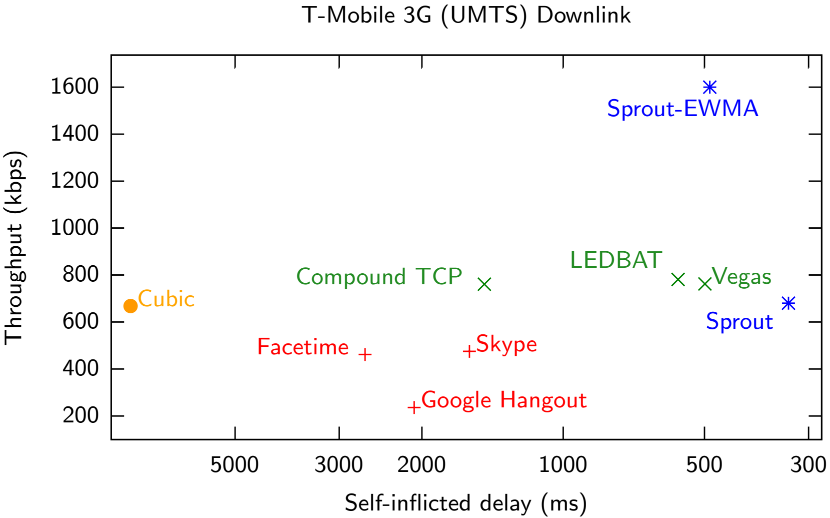


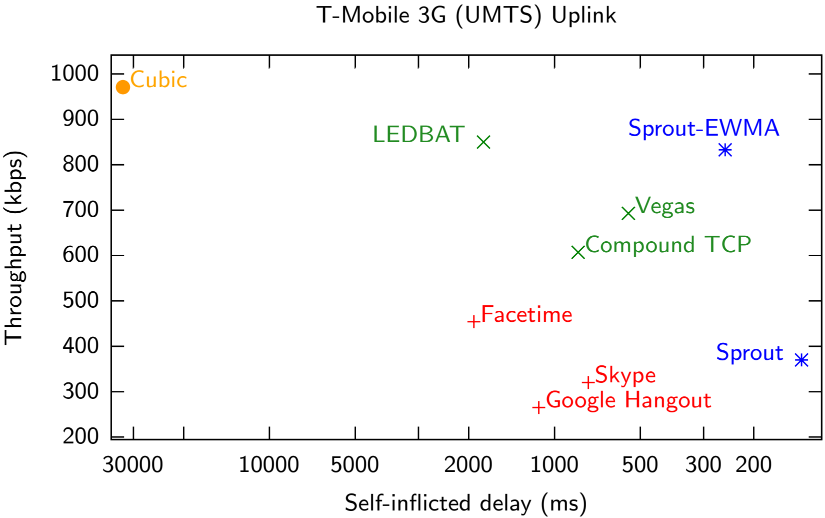

Verizon 3G (1xEV-DO) Downlink
Throughput (kbps)
550
500
450
400
350
300
250
200
150
Self-inflicted delay (ms)
100000
50000
20000
10000
5000
3000
2000
Cubic
Compound TCP
Sprout-EWMA
LEDBAT
Vegas
Sprout
Facetime
Google Hangout
Skype


Verizon 3G (1xEV-DO) Uplink
Throughput (kbps)
600
500
400
300
200
10000
5000
3000
2000
1000
500
300
200
Self-inflicted delay (ms)
Sprout-EWMA
LEDBAT
Skype
Facetime
Vegas
Compound TCP
Google Hangout
Sprout
Cubic


AT&T LTE Downlink
Throughput (kbps)
4000
3500
3000
2500
2000
1500
1000
500
Self-inflicted delay (ms)
5000
2000
1000
500
300
200
100
50
30
Sprout-EWMA
Sprout
Cubic
Facetime
LEDBAT
Compound TCP
Vegas
Skype
Google Hangout


AT&T LTE Uplink
Throughput (kbps)
900
800
700
600
500
400
300
200
20000
10000
5000
2000
1000
500
300
200
Self-inflicted delay (ms)
Cubic
LEDBAT
Sprout-EWMA
Compound TCP
Vegas
Facetime
Skype
Sprout
Google Hangout


T-Mobile 3G (UMTS) Downlink
Throughput (kbps)
1600
1400
1200
1000
800
600
400
200
Sprout-EWMA
LEDBAT
Compound TCP
Vegas
Cubic
Sprout
Facetime
Skype
Google Hangout
5000
3000
2000
1000
500
300
Self-inflicted delay (ms)


T-Mobile 3G (UMTS) Uplink
Throughput (kbps)
1000
900
800
700
600
500
400
300
200
Self-inflicted delay (ms)
30000
10000
5000
2000
1000
500
300
200
Cubic
LEDBAT
Sprout-EWMA
Vegas
Compound TCP
Facetime
Sprout
Skype
Google Hangout