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Once is Never Enough: Foundations for Sound Statistical Inference in Tor Network Experimentation

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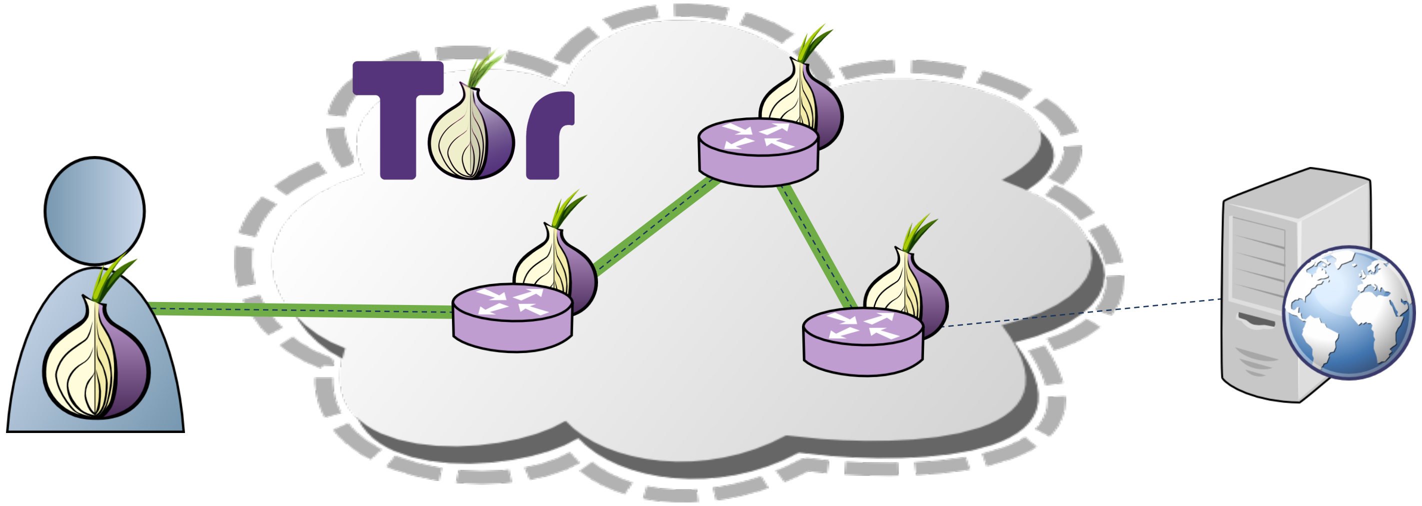
Motivation: Tor Experimentation

Anonymous Communication with Tor

- Separates identification from routing
- Provides unlinkable communication
- Protects user privacy and safety online



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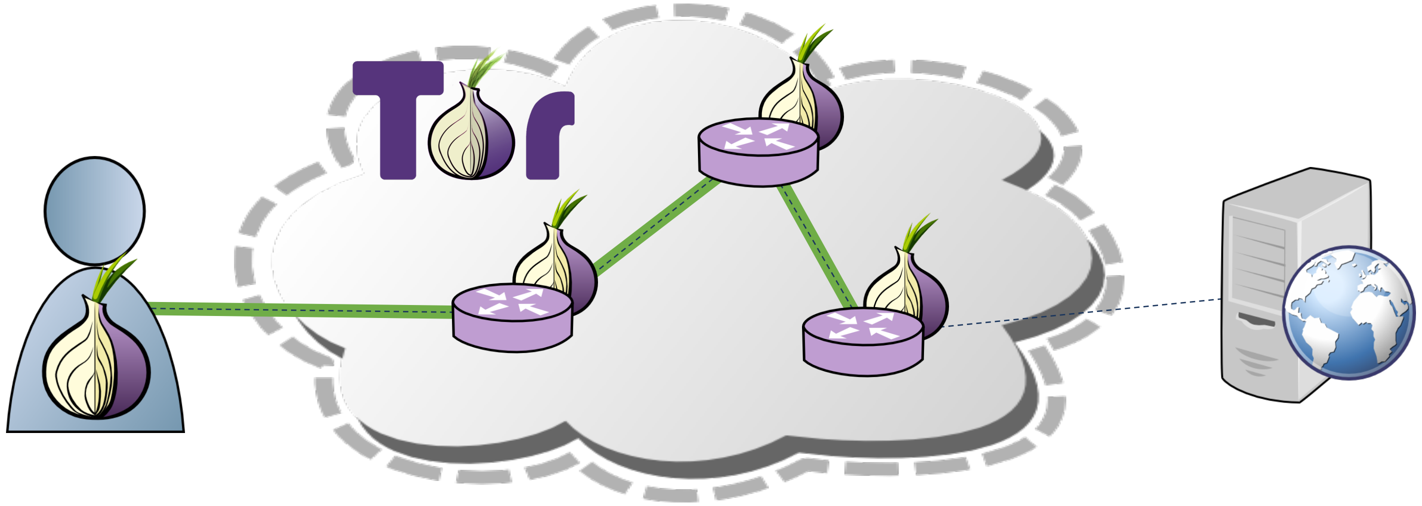

Research to Improve Tor Performance

- A faster Tor means privacy is accessible to more humans
- Many ways to improve performance
- Need methods and tools to help us safely conduct Tor experiments
- We want experimentation results to be accurate and dependable so they can help inform real world decisions

Steps to Run Tor Test Network Experiments

(1) Model a Tor test network configuration

(2) Use Shadow[1] to run Tor experiments

(3) Analyze and compare experimental results

[1]shadow.github.io

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☺ We consider the state of the network *over time* when sampling relays for test networks

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☹ Large RAM and computational requirements

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☹ Previously, one experiment done with vanilla Tor and each research variant

☺ We present methods for quantifying the statistical significance across a set of experiments

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Outline

(1) Model a Tor test network
(2) Use Shadow to run Tor experiments
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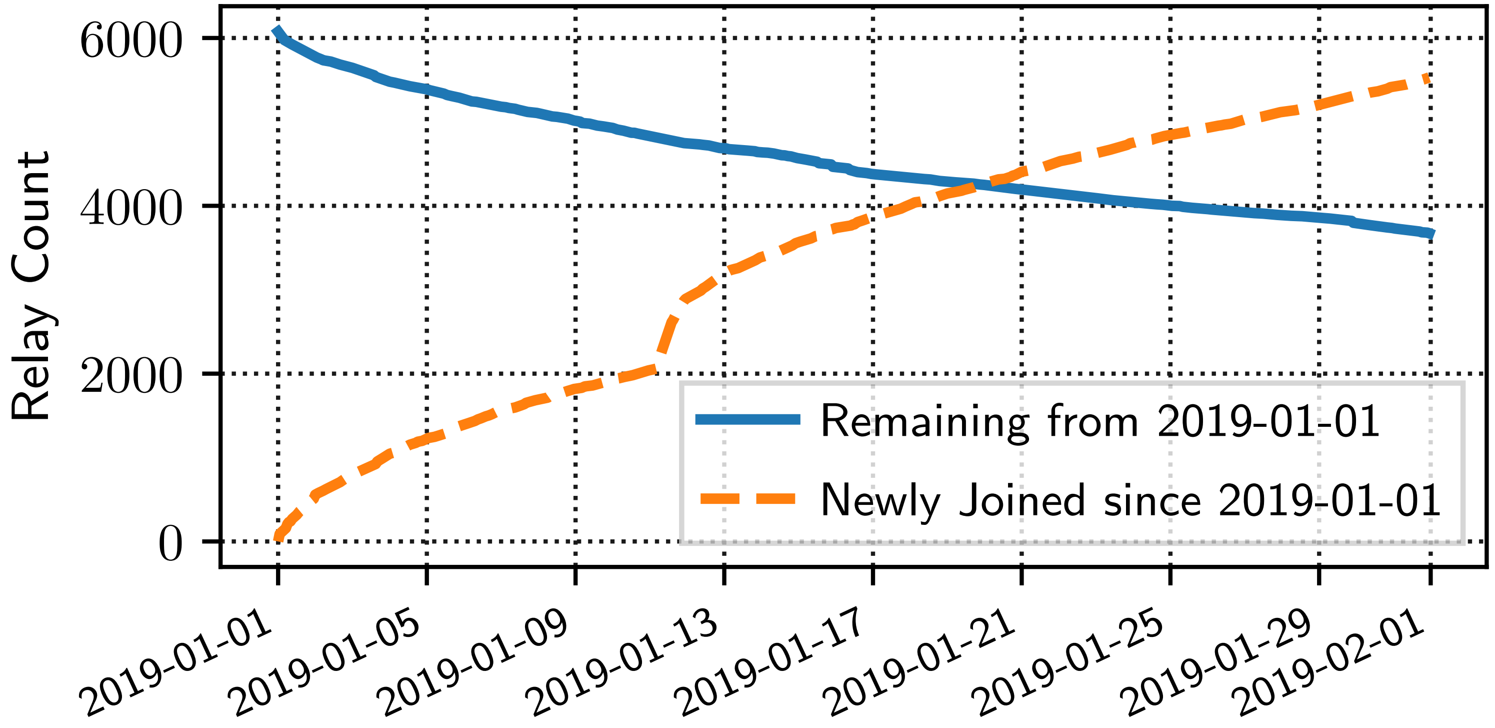
Step (1) Modeling a Tor Test Network

(1) We use data available on metrics.torproject.org to make informed modeling decisions

- The network has high churn



Step (1) Modeling a Tor Test Network

(1) We use data available on metrics.torproject.org to make informed modeling decisions

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- We sample the true relay distribution using the following weights:
  - Relay uptime over the modeling period
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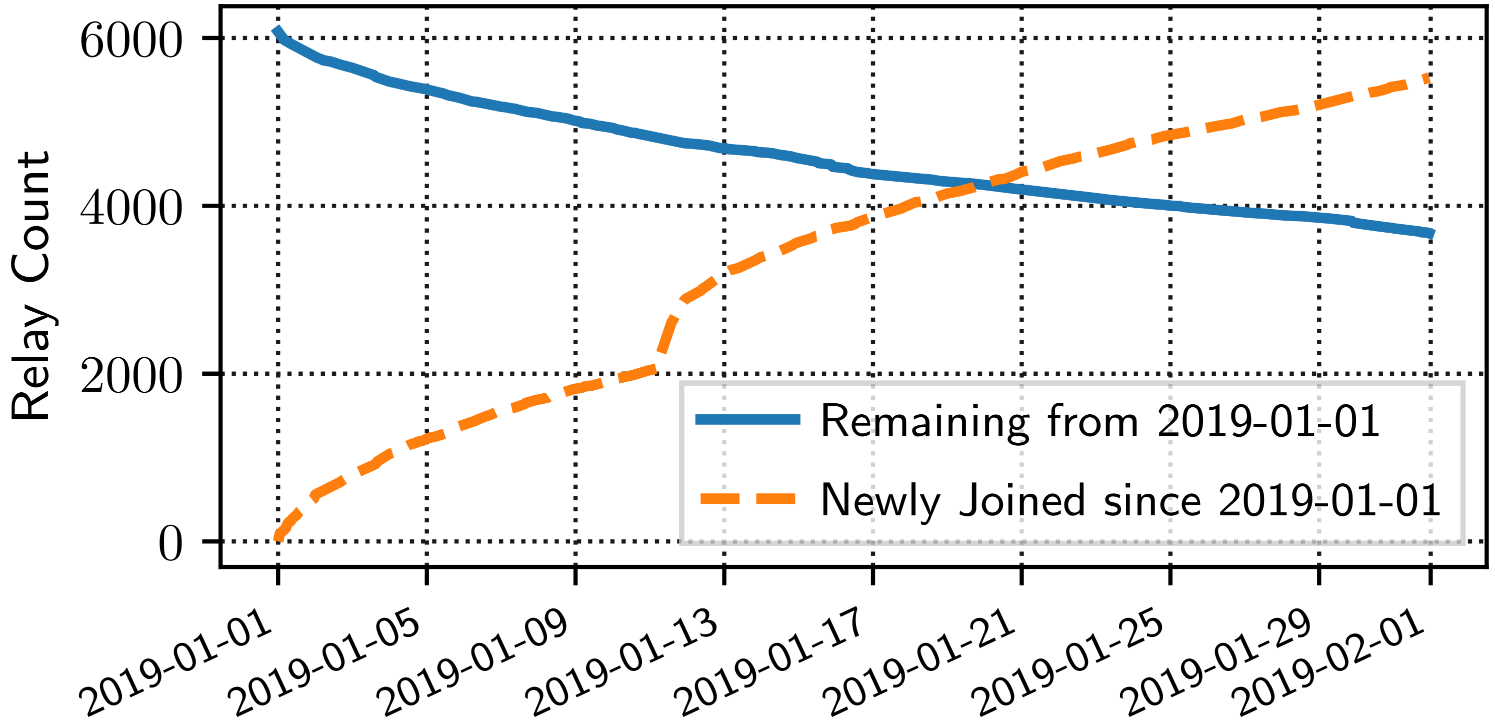

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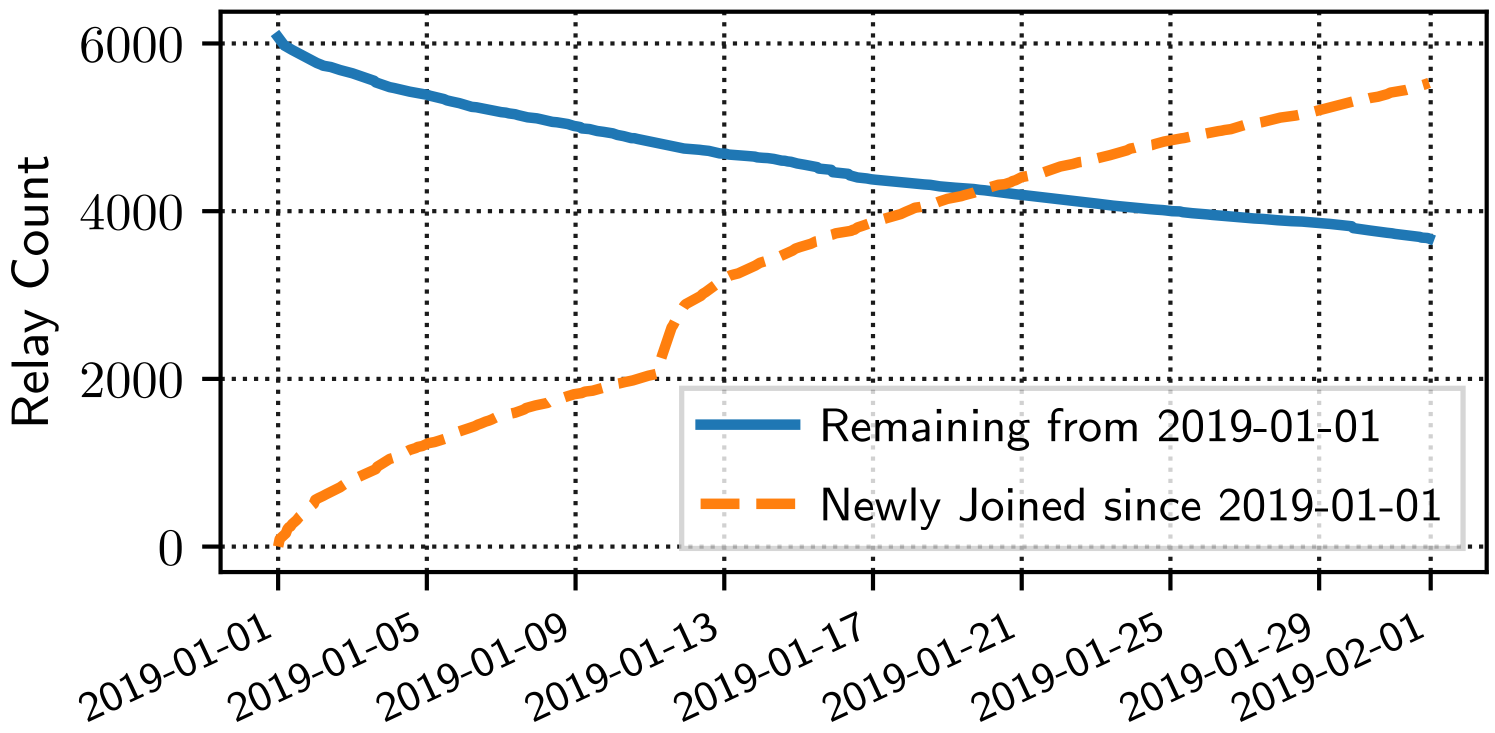

(2) Simulate multiple users in each Tor client process to save RAM

Outline

(1) Model a Tor test network
(2) Use Shadow to run Tor experiments
(3) Analyze and compare experimental results

Step (2) Use Shadow to Run Tor Experiments

- Conducted performance audit of Shadow using the Linux perf tool
  - Fixed several performance bottlenecks
  - Added feature to shorten Tor bootstrapping
  - Enabled run-time optimizations

- Improved Shadow networking
  - Fixed non-determinism bugs
  - Improved network stack

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Table 2: Scalability improvements over the state of the art

Model	Scale $s^\star$	RAM	Bootstrap Time	Total Time	Ω°
CCS'18 [38]†	31%	2.6 TiB	3 days, 11 hrs.	35 days, 14 hrs.	1850
This work†	31%	932 GiB	17 hrs.	2 days, 2 hrs.	79
This work‡	100%	3.9 TiB	2 days, 21 hrs.	8 days, 6 hrs.	310

* **31%**: ≈2k relays and ≈250k users; **100%**: 6,489 relays and 792k users
$^\circ$ Ω: ratio of real time / simulated time in steady state (after bootstrapping)
† Using 8×10-core Intel Xeon E7-8891v2 CPUs each running @3.2 GHz.
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Supports larger test networks

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Running experiments involves two levels of sampling:

1. Sampling a test network model at some scale ≤ 100%
2. Simulating the sampled test network with a seed

Previous work uses one simulation for each research variant

- Ignores sampling error

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Previous work uses one simulation for each research variant

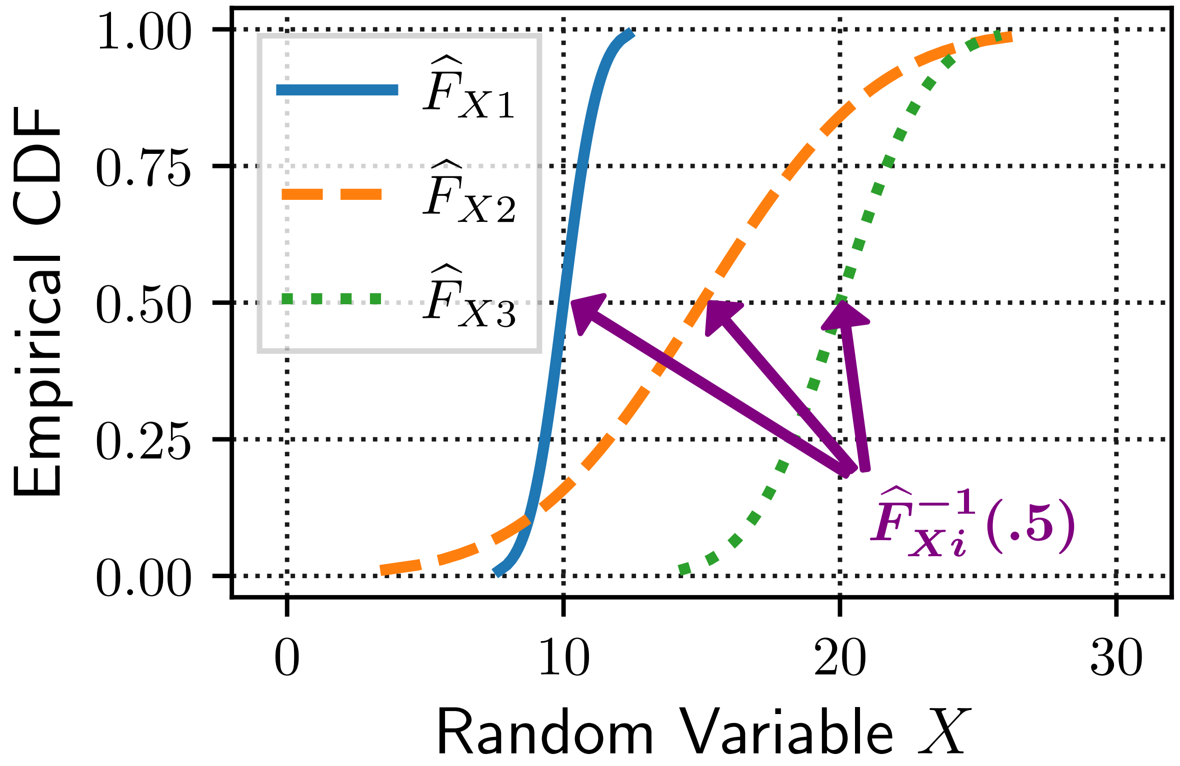
- Ignores sampling error

One simulation is never enough

- We need repeated sampling of test networks (not just sim seeds)
- We quantify the sampling error by computing CIs over empirical CDFs
- Allows us to make statistical arguments for the observed results

Estimating the True CDF with CIs

Each simulation in each test network produces an empirical CDF for our metric of interest



(E.g., time to last byte)

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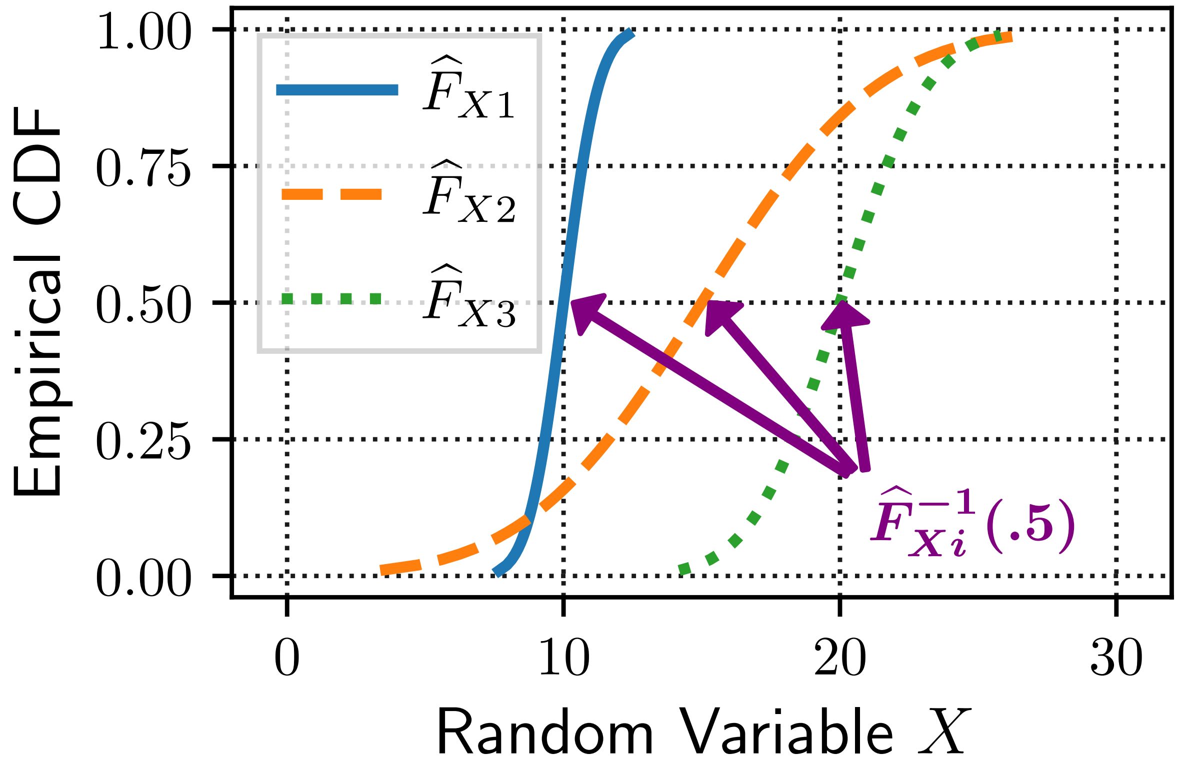

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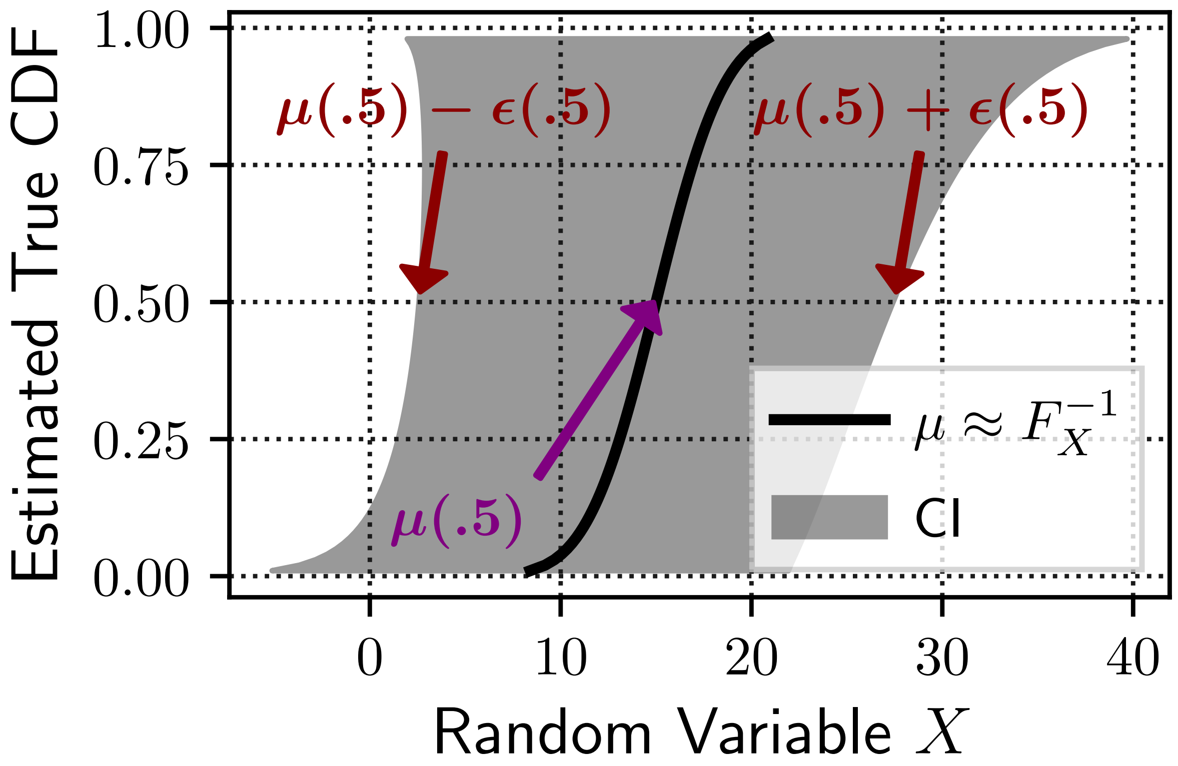
We use the mean to estimate the true CDF, and sampling and measurement error to compute CIs



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Case Study: Tor Usage and Performance

Demonstrate how to apply our methods with an example

Hypothesis:

- Increasing user traffic load by 20% will decrease Tor performance for existing clients

Experiment setup

- 100% and 120% traffic loads
- 1%, 10%, and 30% scale factors
- 420 total simulations

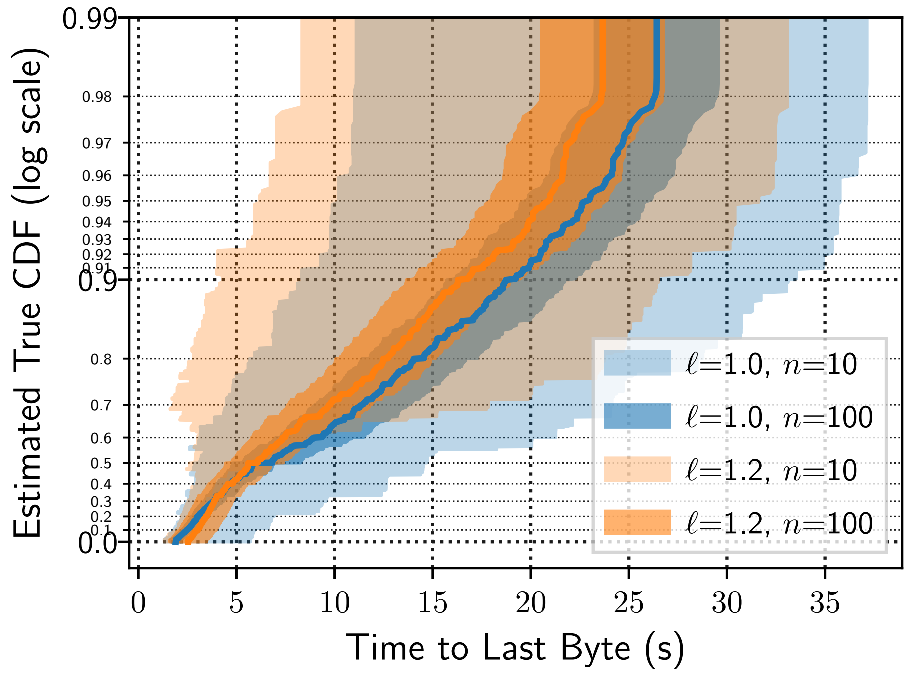
Scale	Load	Number of Simulations
1%	100%	100
1%	120%	100
10%	100%	100
10%	120%	100
30%	100%	10
30%	120%	10

How does network scale affect the conclusions we can draw from the results?

CIs Inform the Analysis of Results

Scale = 1%

CIs overlap even with 100 sims



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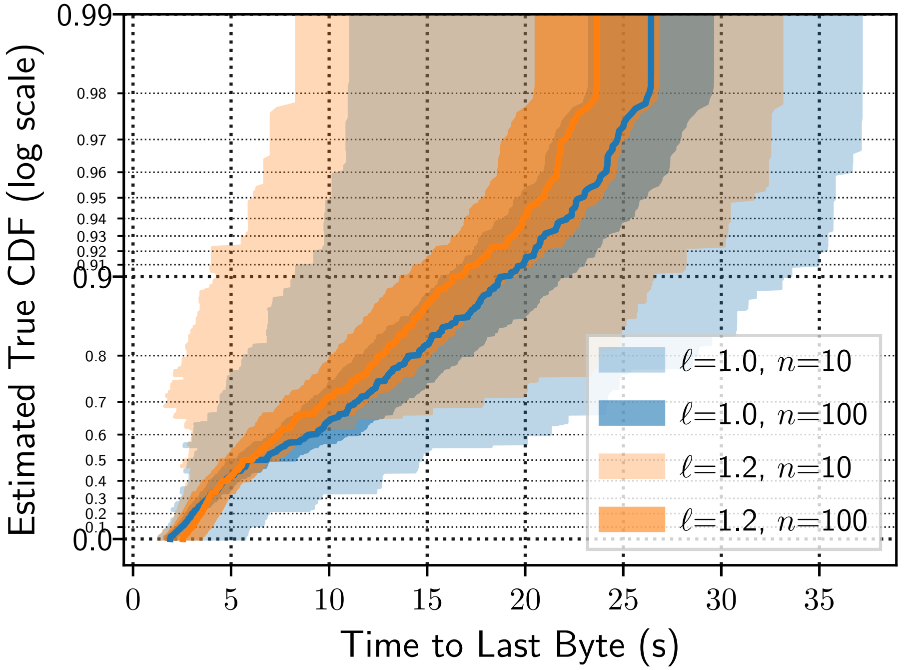
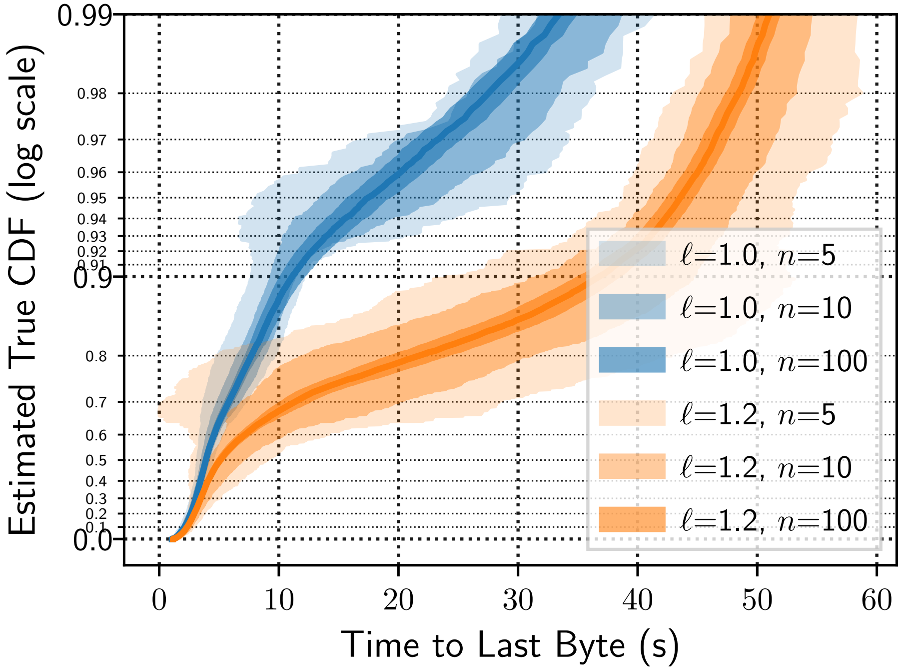


Scale = 10%

CIs are close with 5 sims, but separate with 10 sims



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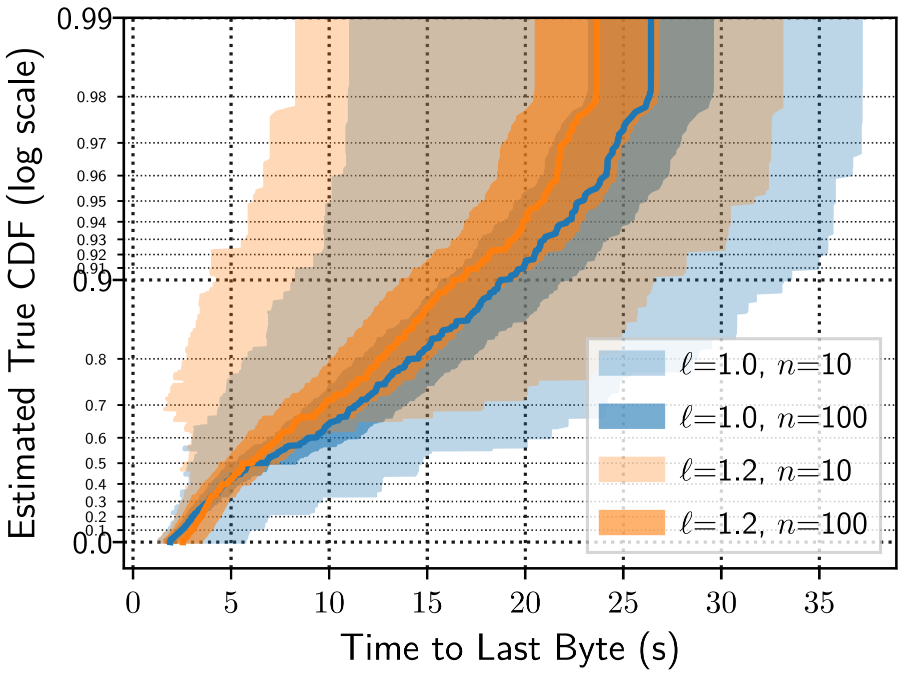

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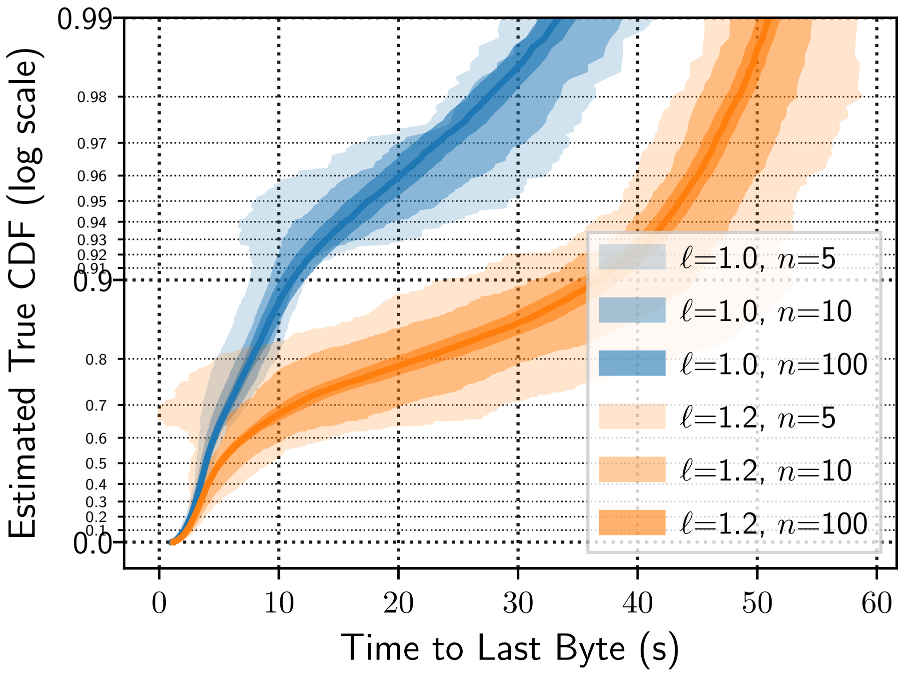
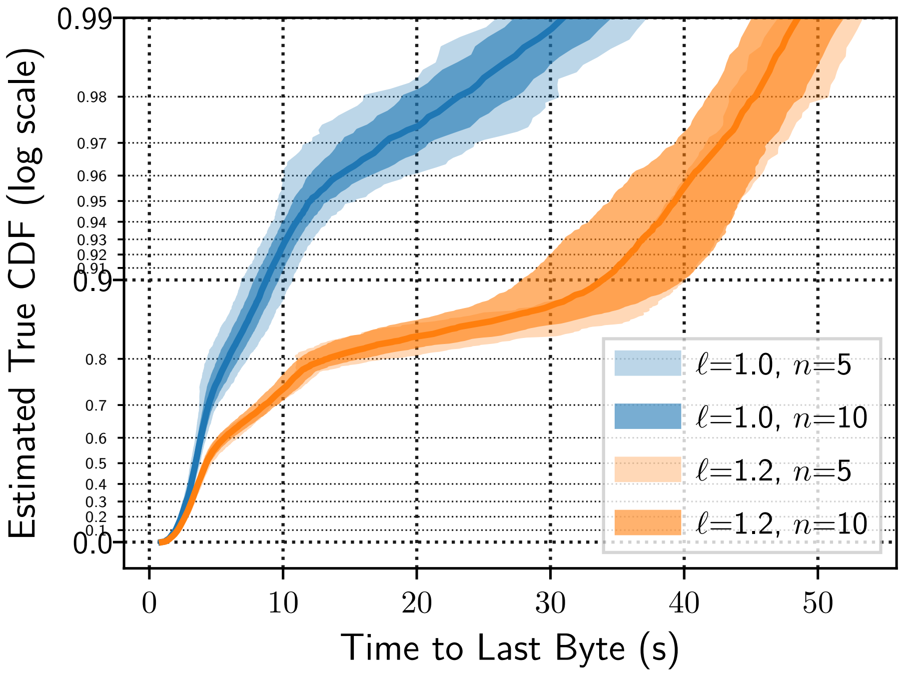


Scale = 30%

CIs clearly separate with either 5 or 10 sims



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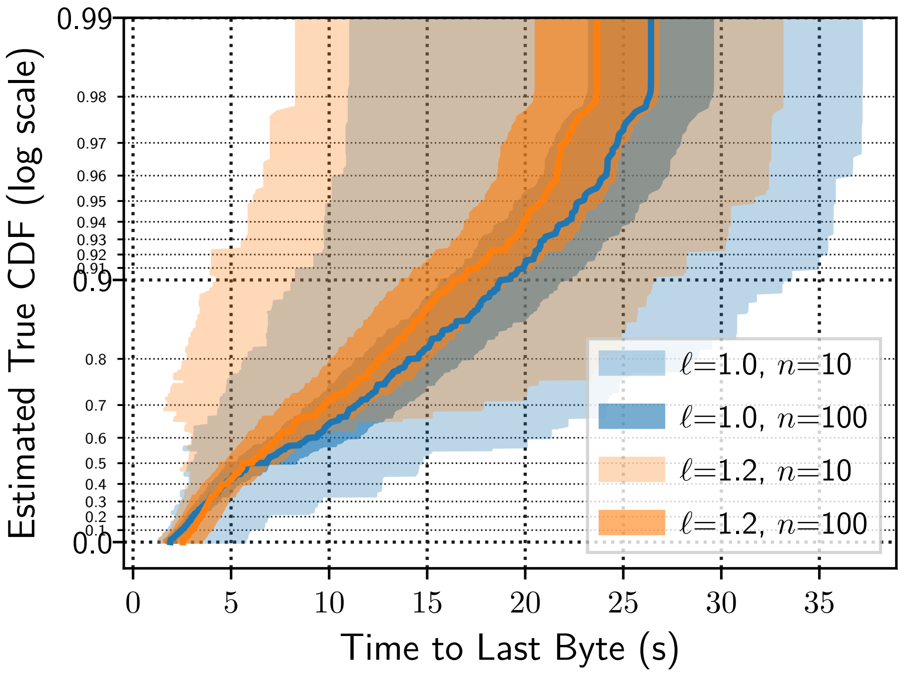

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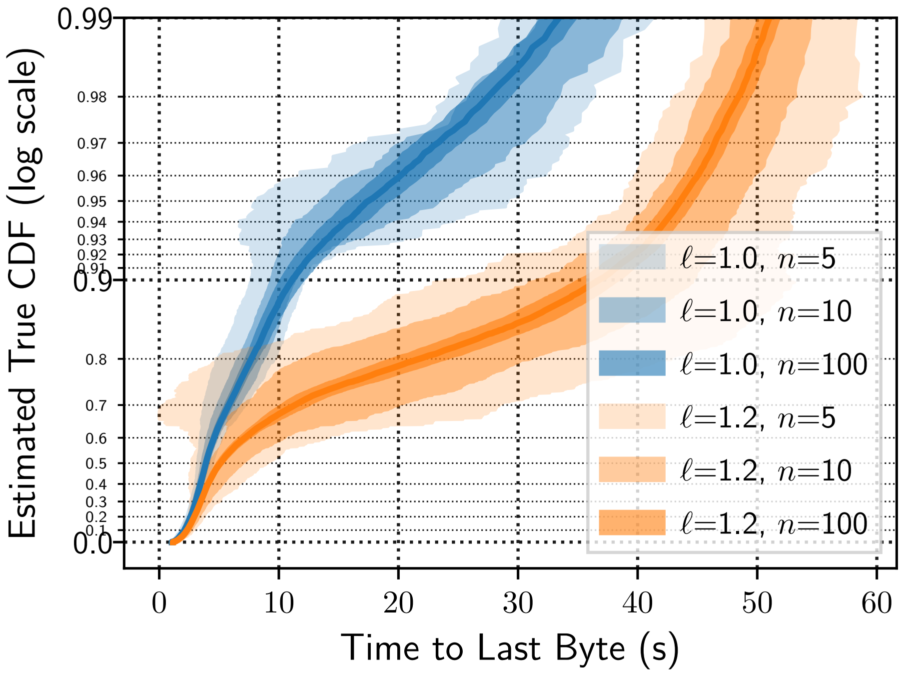

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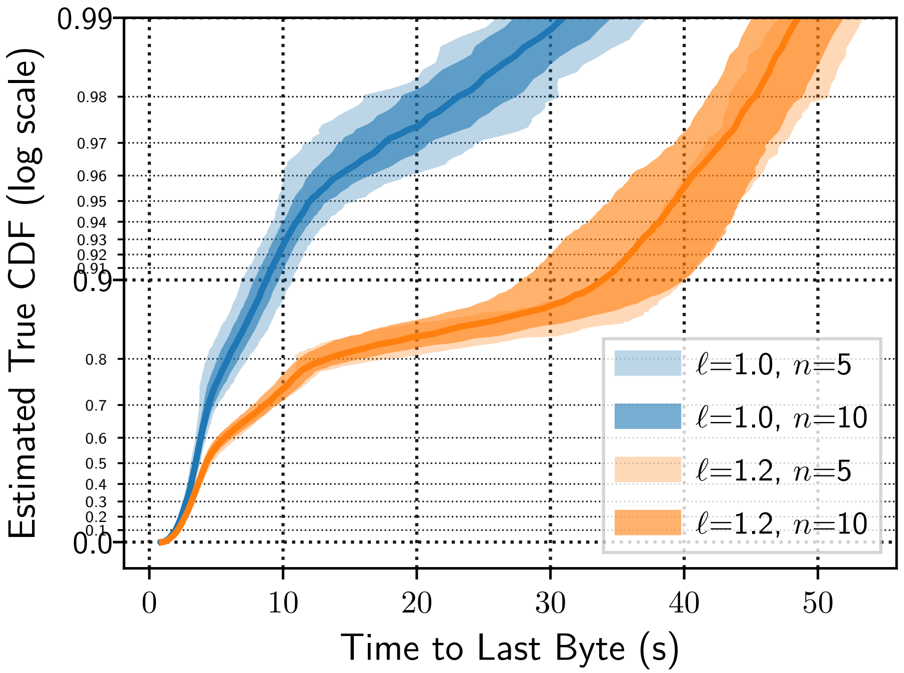

More simulations needed at smaller scales, fewer at larger scales to reach a certain CI precision

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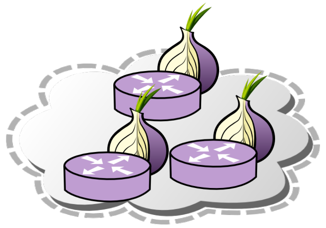
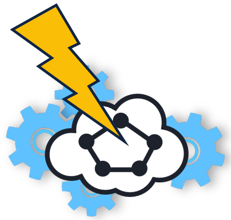
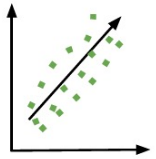
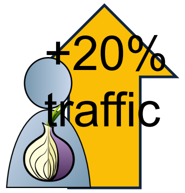
Summary

Primary Contributions	Main Results
(1) New methods for constructing Tor test networks considering the state of the network over time rather than at a static point	We create many test Tor networks in Shadow → a Tor network with up to 6,489 relays → traffic of up to 792k simultaneously active users
(2) New/improved experimentation tools, optimized to run Tor faster and at larger scales than previously possible	We enhanced Shadow to reduce: → RAM usage by 64% → run time by 94%
(3) New methodology for conducting statistical inference using results collected from experiments in smaller-scale Tor networks	Running multiple simulations in independently sampled Tor networks → necessary for statistical significance
(4) Demonstrated how to apply our methodologies to conduct sound Tor performance research	To reach a desired precision requires: → more simulations in smaller-scale networks → fewer simulations in larger-scale networks

Artifacts: https://neverenough-sec2021.github.io

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