BrowsEm: Model-based Web Site Loading Emulation

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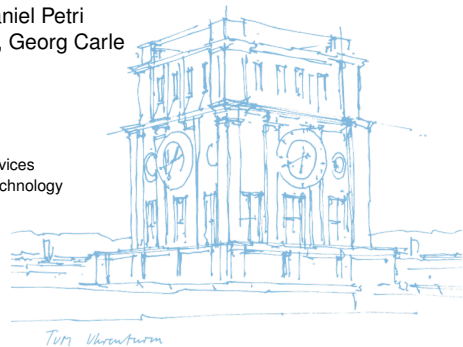

Web protocol research commonly based on prototypes and measurements

Fully synthetic evaluations:

- Allows for targeted understanding of behavior
- Unknown effect on complex web applications

In-browser measurements:

- Complex software systems, hard to modify
- Flexibility? Reproducibility?

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BrowsEm:
Emulator for reproducing network activity during web site loading

- Model of recorded browser behavior and request dependencies
- Emulation of network path characteristics
- Flexible support for wide range of standards and implementations, e. g., HTTP, QUIC, or TLS
- Wide-spread components (e. g., libcurl) and modifiable building blocks

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⇒ Reproducible measurement platform for realistic web workloads

- For **protocol researchers:** Assessment of experimental implementations
- For **web site operators:** Evaluation of deployment changes

Related Work: Approaches for Web Traffic Modeling

Analytical models

- Statistical models of user interaction with website, e. g., [1, 7, 5]
- Commonly derived from Internet measurements, e. g., SURGE [2] or others [6, 10]
- Implemented in `ns-3` simulator module [9]

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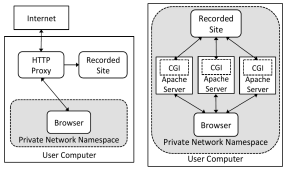
Trace-based

- “Record and replay” of HTTP requests
- Mahimahi [8]
  - Proxy to record HTTP requests
  - Network emulation, supporting multiple connections
  - Browser for loading website



(a) RecordShell (b) ReplayShell

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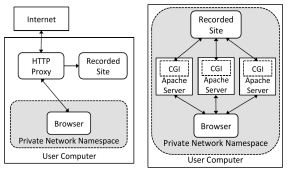

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This work

- Trace-based
- Includes request dependencies
- Additional modeling parameters
- Not browser based, allows for protocol modifications

Approach

1. Scraping
   - devtools[1]-controlled headless Chromium browser
   - Write key log file
   - Export HTTP Archive (HAR) file containing detailed request information, such as
     - HTTP header information
     - Request subtimings: *blocked*, *dns*, *connect*, *tls*, *send*
   - Traffic sniffing
     - PyShark[2] to decrypt and analyze
     - Estimation of path RTT: TCP `tsopt`, handshake timestamps, ICMP echo request / reply, (QUIC spin bit)
     - Estimation of path capacity: PPrate [4, 3]

[1] https://chromedevtools.github.io/devtools-protocol/

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2. Modeling

- Replace interpretation of received data with delay and transaction dependency information
- HAR *initiator* field, complemented by timing inference
- Request and response timings, headers, and body sizes
- Network path parameters (delay, capacity, loss)
- Stored as editable JSON configuration file

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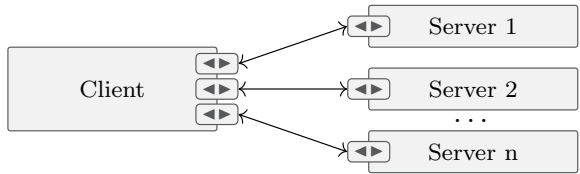
Approach

3. Emulation

- Linux namespaces and NetEm for separate paths
- Rust application, asynchronous tasks for each server, client, and transaction
- Included server options:
  - Actix web for HTTP/1.0, HTTP/1.1, HTTP/2
  - quinn for HTTP/3
  - nginx
- Client
  - libcurl through bindings
  - Five QUIC libraries available
  - Requests started in accordance with timing information



4. Postprocessing

Evaluation

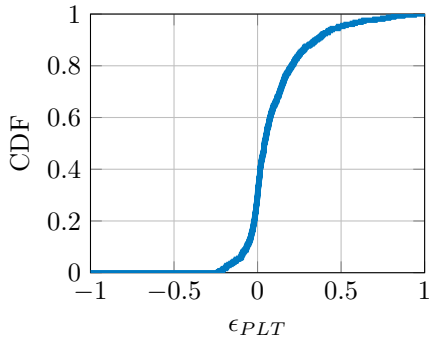
Goals: Assess emulation quality

Dataset: Top 1000 web sites[3], 922 usable samples

Approach:
- Assess page load time (PLT)
- Compare subtimings of scraped and emulated web sites
- Investigate model stability

[3] https://www.domcop.com/top-10-million-domains

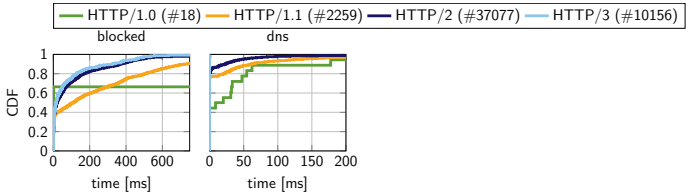
Evaluation: Page Load Time



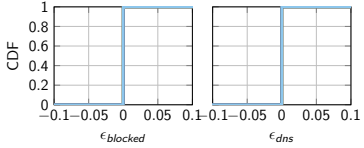
Relative differences $\epsilon_{PLT} = \frac{s_{PLT} - e_{PLT}}{s_{PLT}}$ of scraped s_{PLT} and emulated PLT e_{PLT}

- $\approx$ 80% page loads have less than $\pm 0.25 \epsilon_{PLT}$
- Well met dependency tree of requests and timings

Evaluation: Transaction Subtimings



Transaction phase durations of scraped data set



Relative difference to emulation; $\epsilon_P = \frac{s_P - e_P}{s_P}$

- *blocked* and *dns* are met

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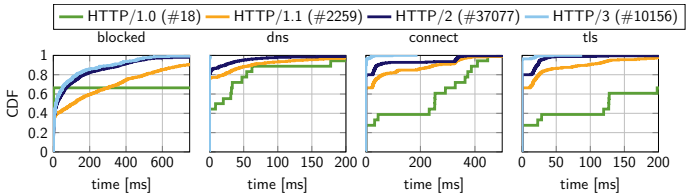

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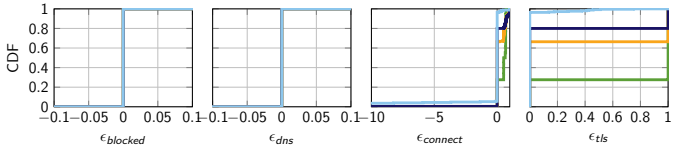

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- Faster emulation
- Crypto libraries? RTT estimates?

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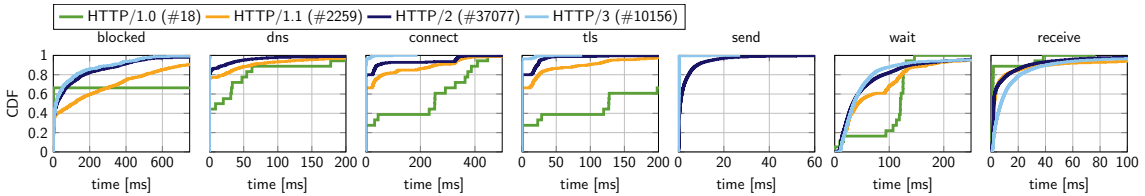

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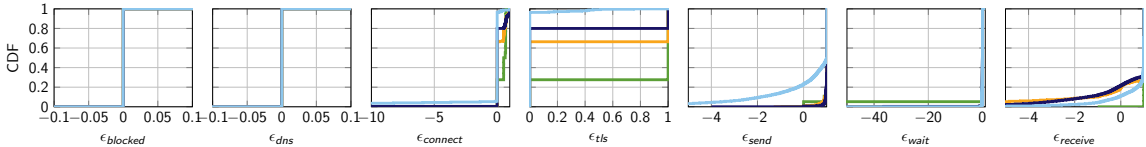

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- *wait* is mostly met, emulator depends on RTT
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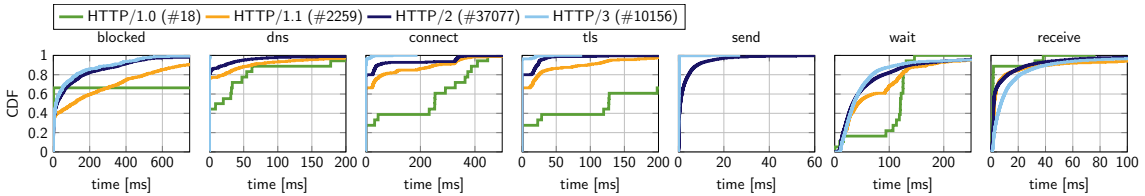

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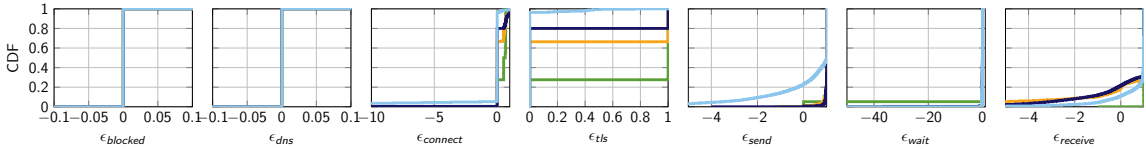

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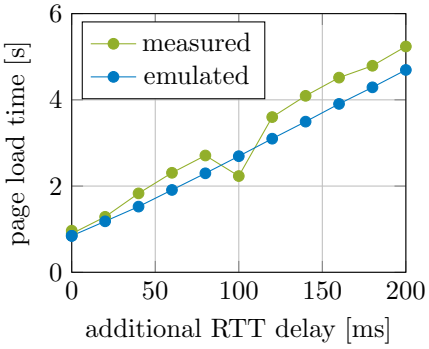
⇒ Transaction phases are emulated reasonably well

Evaluation: Stability Analysis with Changed RTT



- Alter RTT parameter of emulation model
- Scrape same site with added delay as ground-truth
- Emulation follows trend of measurement
- Model captures impact of RTT on PLT

Limitations and Future Work

- Inherent limitations
  - Browser behavior (e. g., JS execution, rendering) captured implicitly
- More model parameters
- Improve quality of parameter estimation
  - Path RTT and capacity estimation
  - Complement browser-reported timing with network trace information
- Add and use more information sources (e. g., packet traces)
  - Chunked / application limited transmissions
- Support other browser with similar interfaces, e. g., Firefox
- Broader stability testing

Conclusion

- Network workload emulator for web applications
- Focus on transport and HTTP application layer
- Solves orchestration and reproducibilty
- Extensible design, ready for your prototype
- Useful for protocol research or performance optimization

Slides (pdf)[4]

Paper (pdf)[5]

Code[6]

[4] http://www.net.in.tum.de/fileadmin/bibtex/publications/papers/holzinger2025browsem_slides.pdf

[5] http://www.net.in.tum.de/fileadmin/bibtex/publications/papers/holzinger2025browsem.pdf

[6] https://github.com/holzingk/BrowsEm/

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