FTZ: A State-Inferring Fuzzer for the TCP/IP Stack of Zephyr

Master's Thesis

Valentin Huber, 28.02.2025

Agenda

Background

Real-Time Operating System

Open Source

Zephyr

Networking is Central

Widely Used

Repeated Execution of a Target
with Random(-ish) Inputs

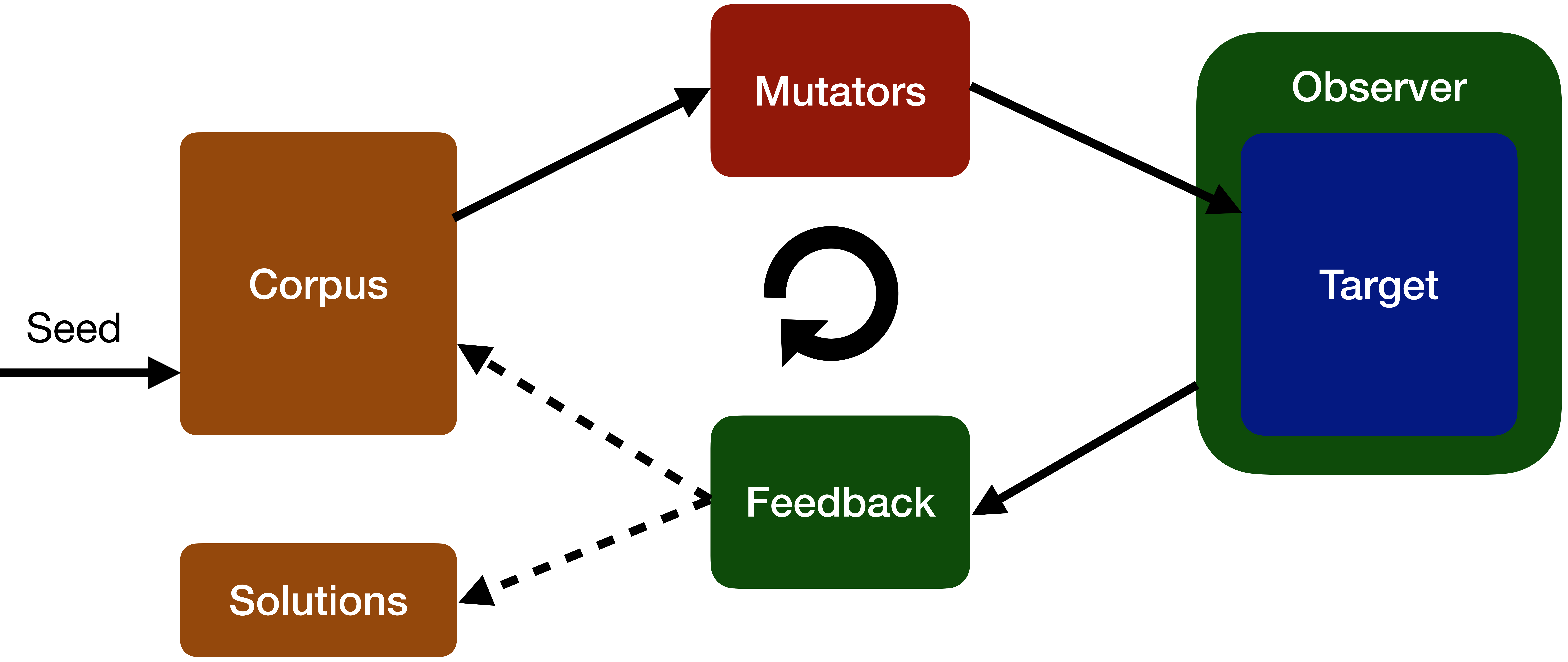
Significant Developments

Fuzzing

Widely Used and Proven Effective

Looking for Illegal Program States

Mutational Fuzzing



Fuzzing OS Network Stacks Is Hard

Fuzzing OS Network Stacks Is Hard

- Deep Integration with Operating System

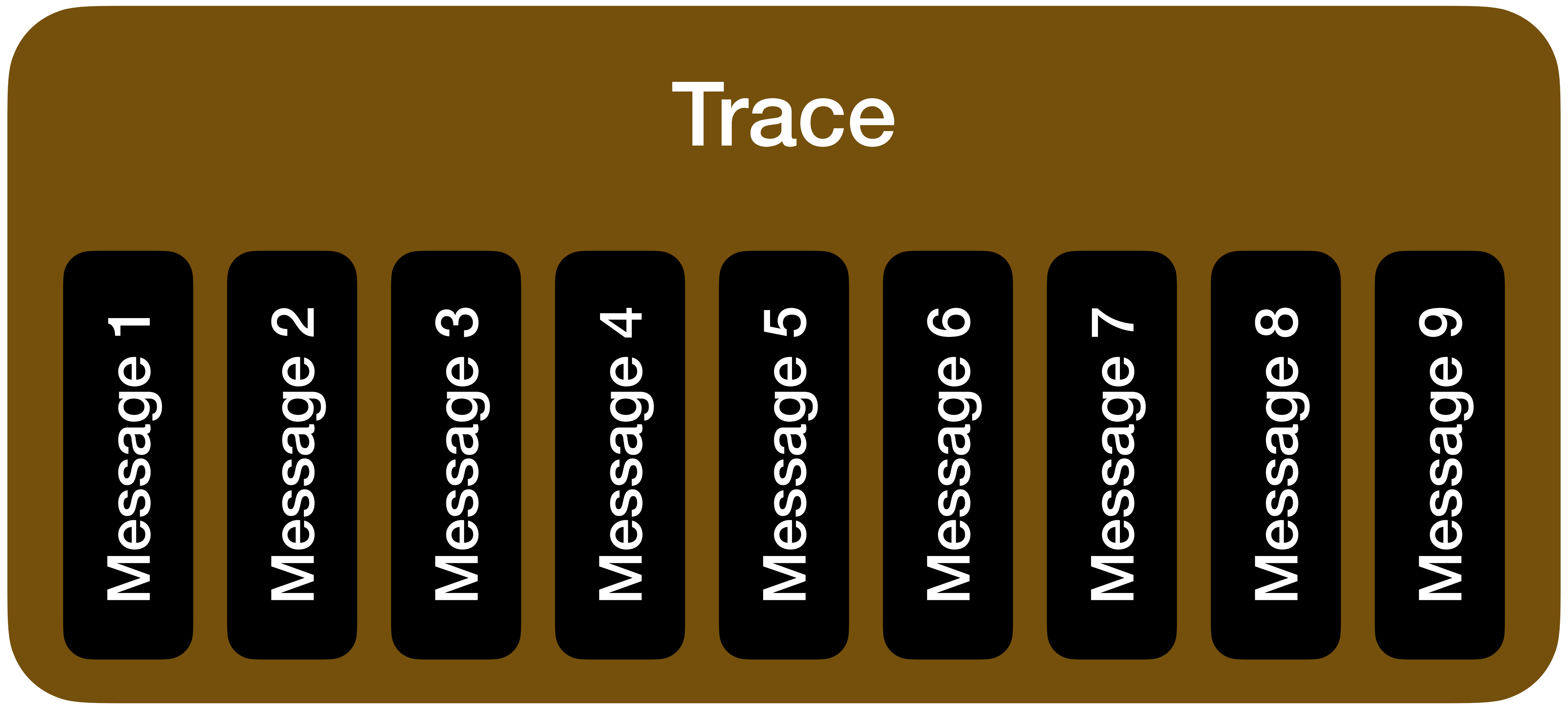
Fuzzing OS Network Stacks Is Hard

- Deep Integration with Operating System
- Network Packets Are Highly Structured

Layer	Ethernet				IPv4												TCP										Payload	Ethernet
Field	Destination MAC	Source MAC	802.1Q VLAN Tag	EtherType	Version	Internet Header Length	DSCP & ECN	Total Length	Identification	Flags & Fragment Offset	Time To Live	Protocol	Header Checksum	Source IP	Destination IP	Options	Source Port	Destination Port	Sequence Number	Acknowledgment Number	Data Offset & Reserved	Flags	Window	Checksum	Urgent Pointer	Options	Payload	Frame Check Sequence
Size	6	6	4	2	1	1	1	2	2	2	1	1	2	4	4	var	2	2	4	4	1	1	2	2	2	var	var	4

Fuzzing OS Network Stacks Is Hard

- Deep Integration with Operating System
- Network Packets Are Highly Structured
- TCP Stacks Have Internal State



Contributions: 27 PRs, 10,000 LoC

Fuzzing Library in Rust

LibAFL

Advanced Implementations

Common Structures

Incompatible Improvements

Related Works

TCP-Fuzz

FitM

Implementation

Implementation

- native_sim
- SanitizerCoverage
- Custom Ethernet Driver
- Input Modeling and Mutation

Input Modeling and Mutation

- Message Modeling

Layer	Ethernet				IPv4												TCP										Payload	Ethernet
Field	Destination MAC	Source MAC	802.1Q VLAN Tag	EtherType	Version	Internet Header Length	DSCP & ECN	Total Length	Identification	Flags & Fragment Offset	Time To Live	Protocol	Header Checksum	Source IP	Destination IP	Options	Source Port	Destination Port	Sequence Number	Acknowledgment Number	Data Offset & Reserved	Flags	Window	Checksum	Urgent Pointer	Options	Payload	Frame Check Sequence
Size	6	6	4	2	1	1	1	2	2	2	1	1	2	4	4	var	2	2	4	4	1	1	2	2	2	var	var	4

Input Modeling and Mutation

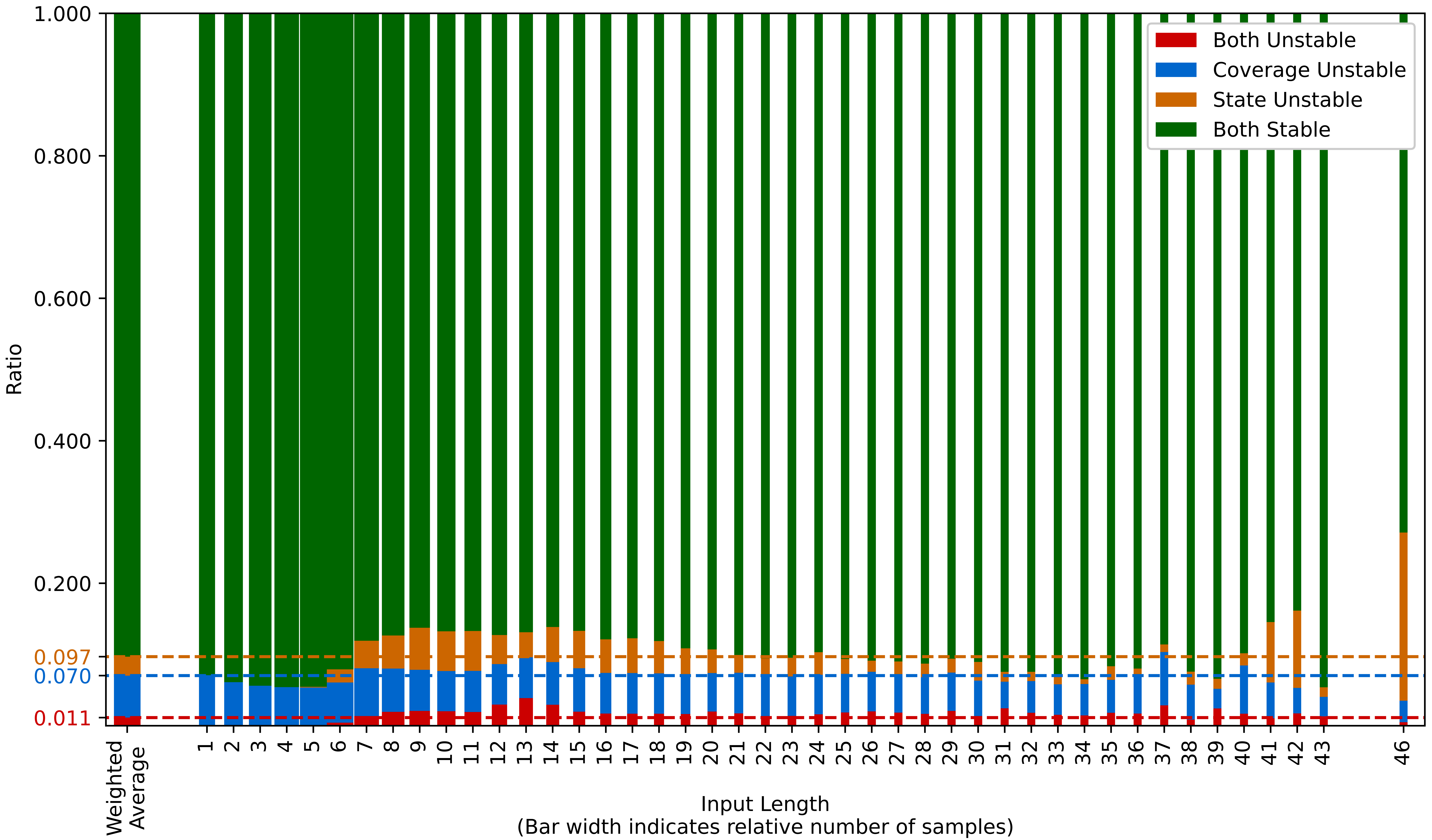
- Message Modeling
- Trace Modeling
- Appending Mutators

Implementation

- native_sim
- SanitizerCoverage
- Custom Ethernet Driver
- Input Modeling and Mutation
- State Inference

Evaluation

Zephyr behaves inconsistently

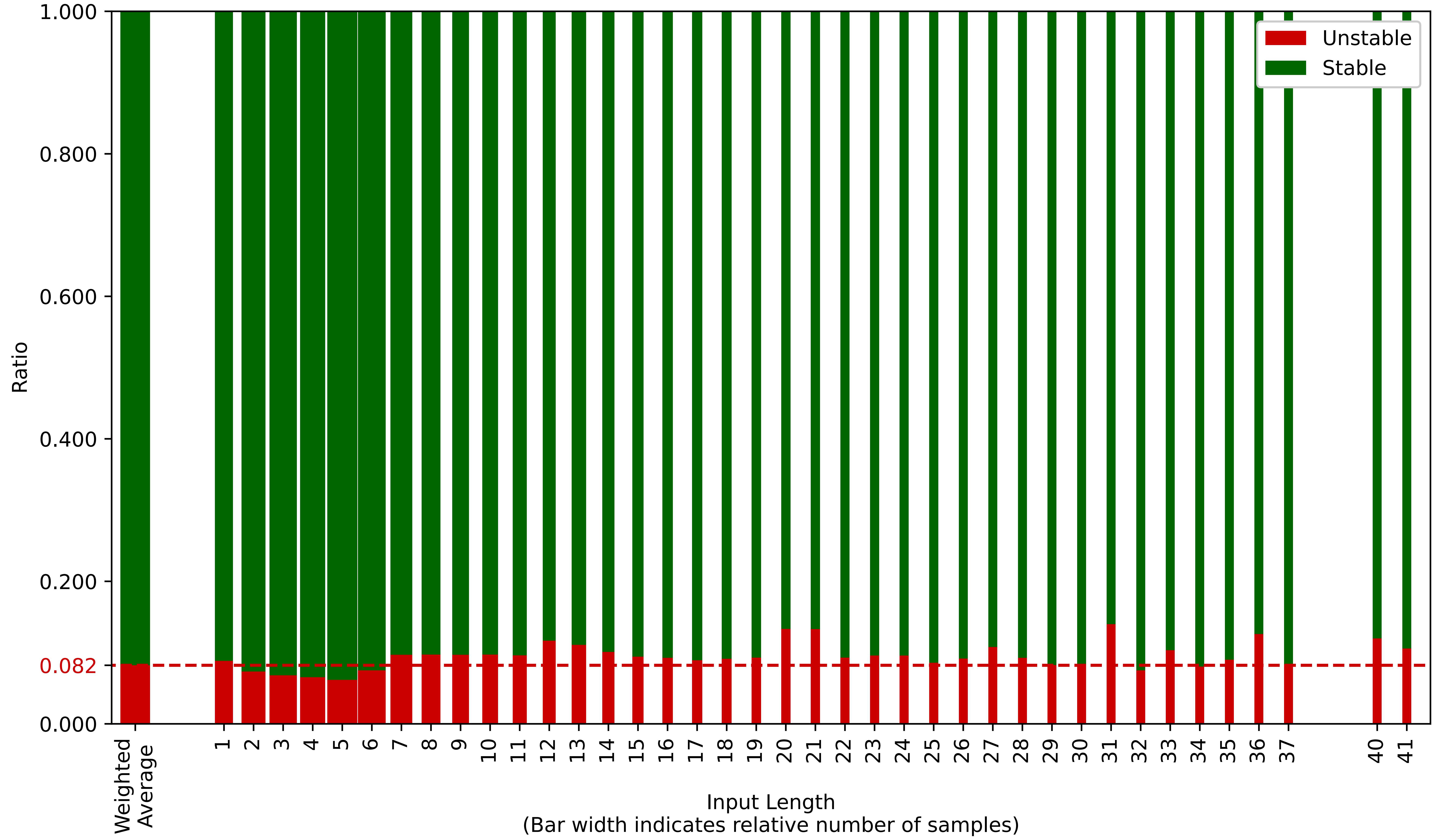


1.000
0.800
0.600
0.400
0.200
0.097
0.070
0.011
Ratio
Both Unstable
Coverage Unstable
State Unstable
Both Stable
Weighted Average
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 46
Input Length
(Bar width indicates relative number of samples)

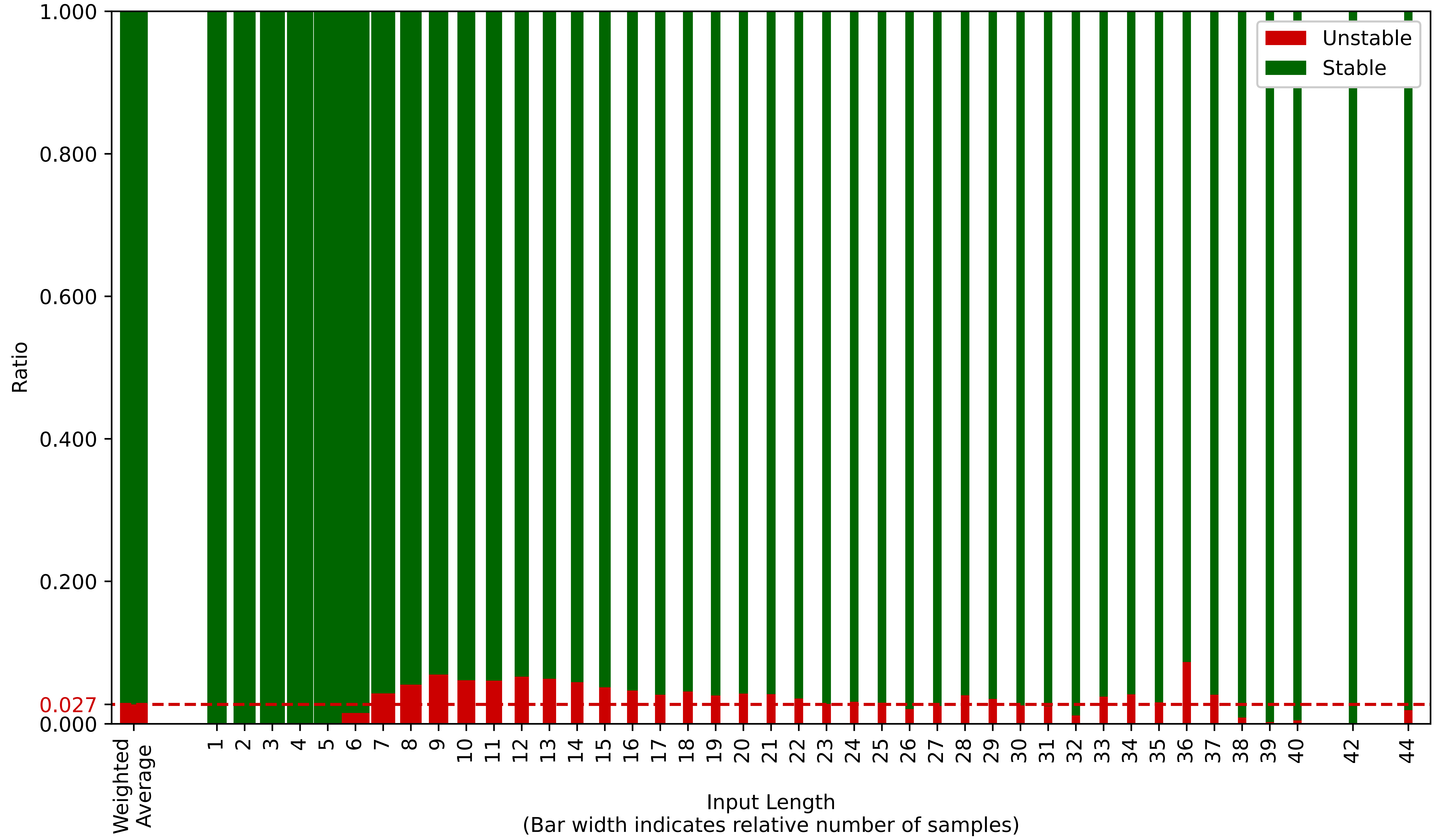
Coverage Is Inconsistent

1. `k_work_init_delayable` from `kernel/work.c`
2. `net_ipv6_mld_init` from `net/ip/ipv6_mld.c`
3. `sys_slist_init` from `sys/slist.h`
4. `z_slist_tail_set` from `sys/slist.h`
5. `net_conn_init` from `net/ip/connection.c`

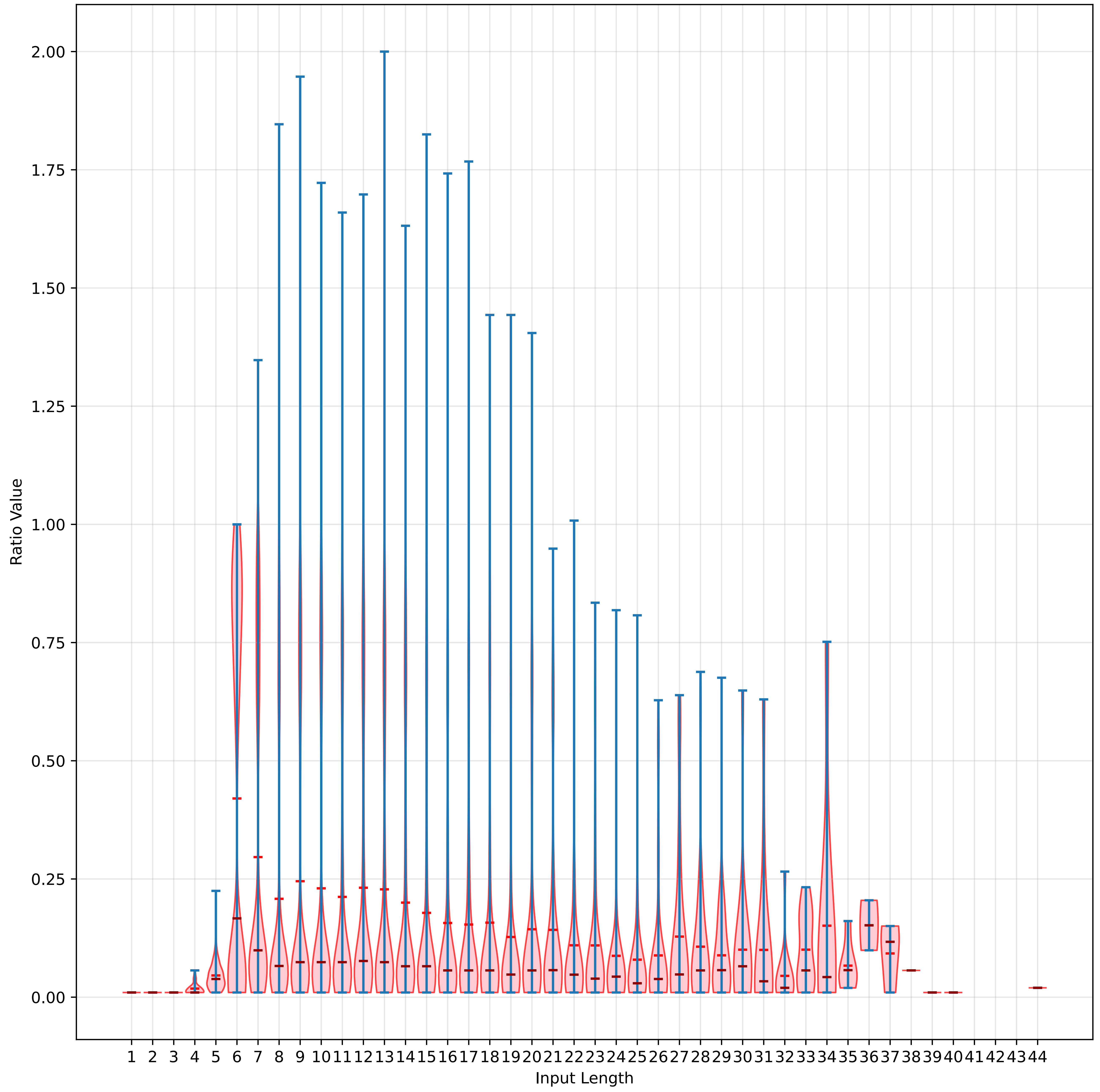
Coverage Is Inconsistent



Packet Responses Are Inconsistent



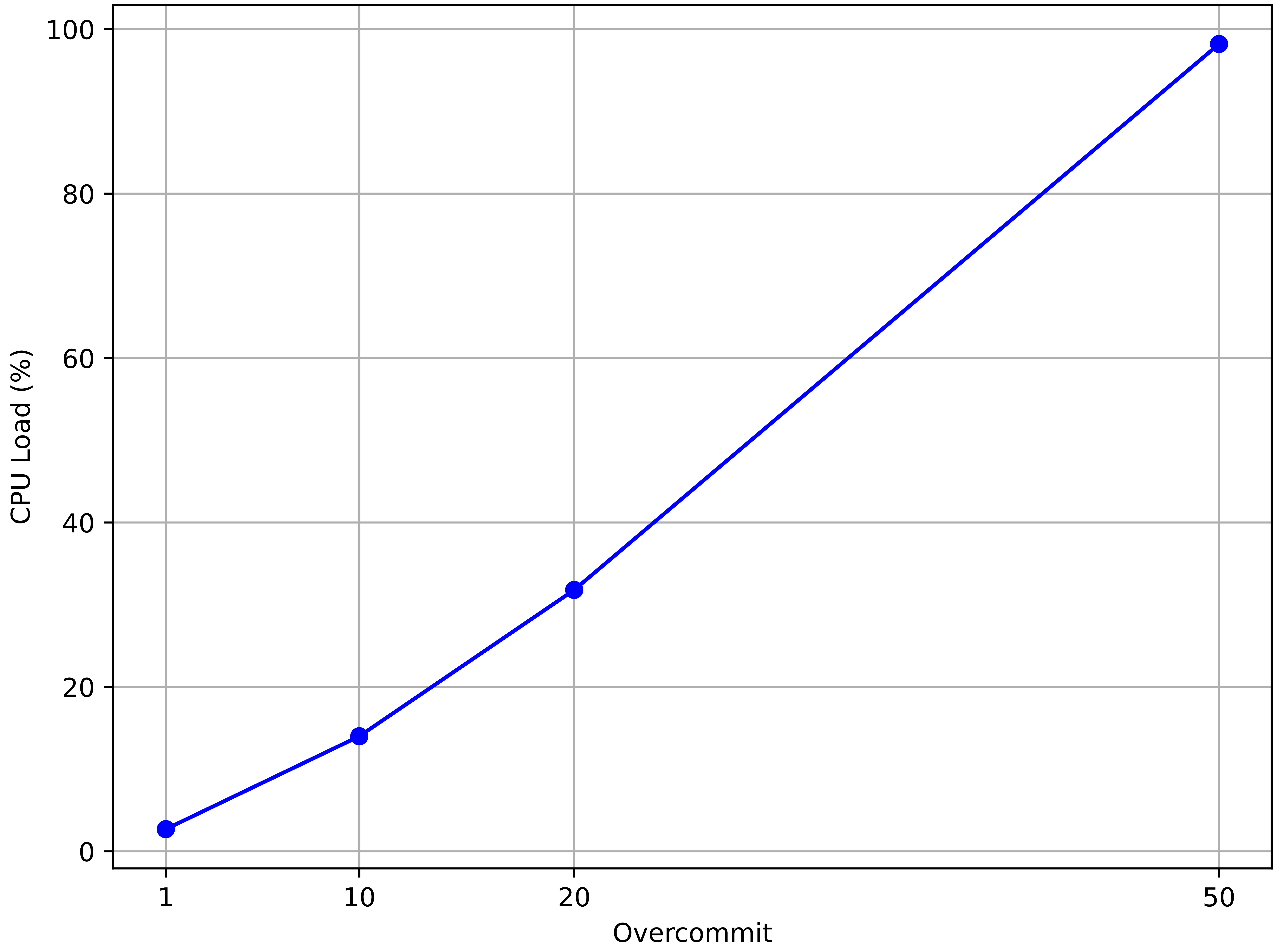
State Is Inconsistent



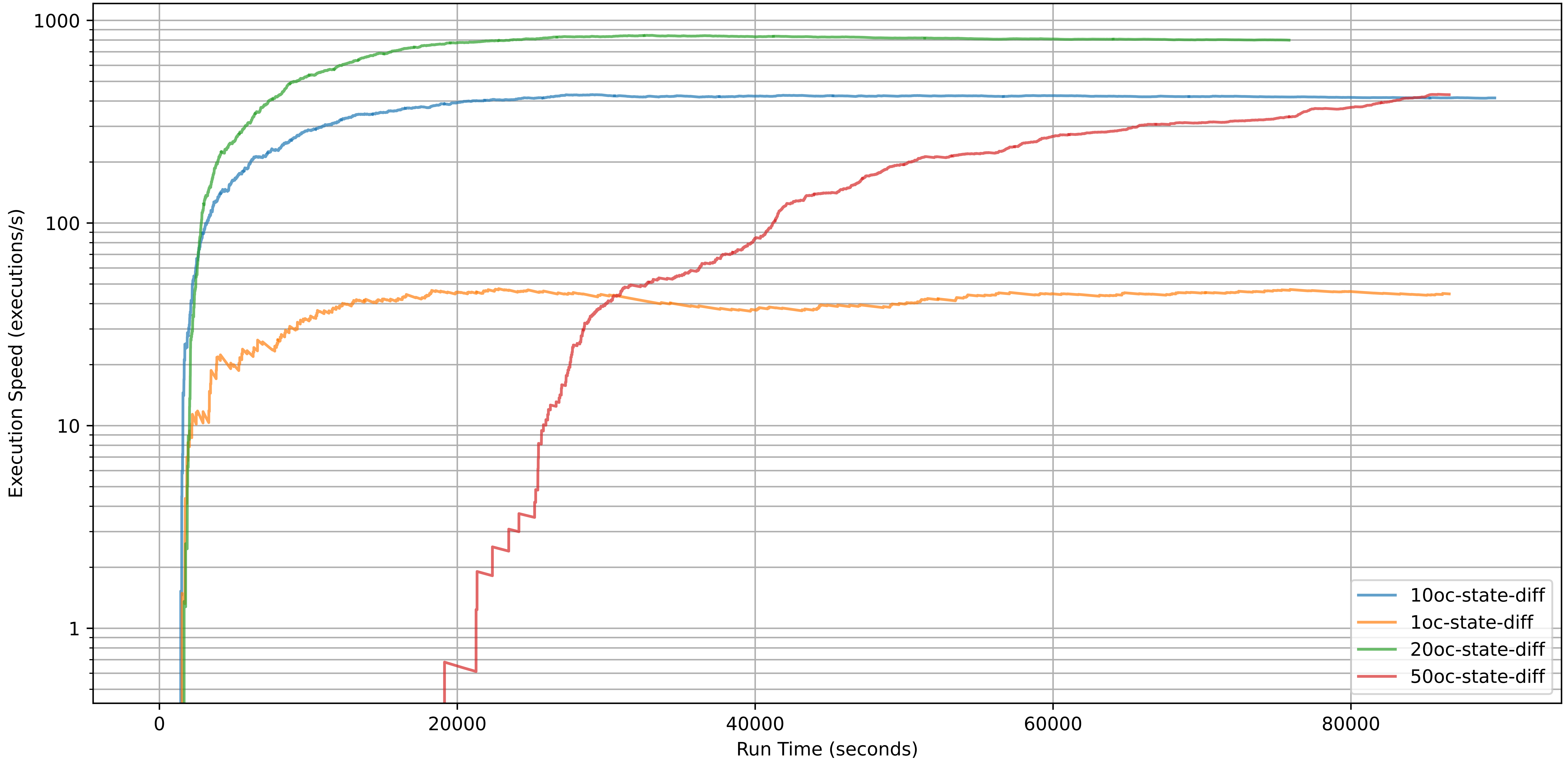
Zephyr behaves inconsistently

Overcommit

Overcommit

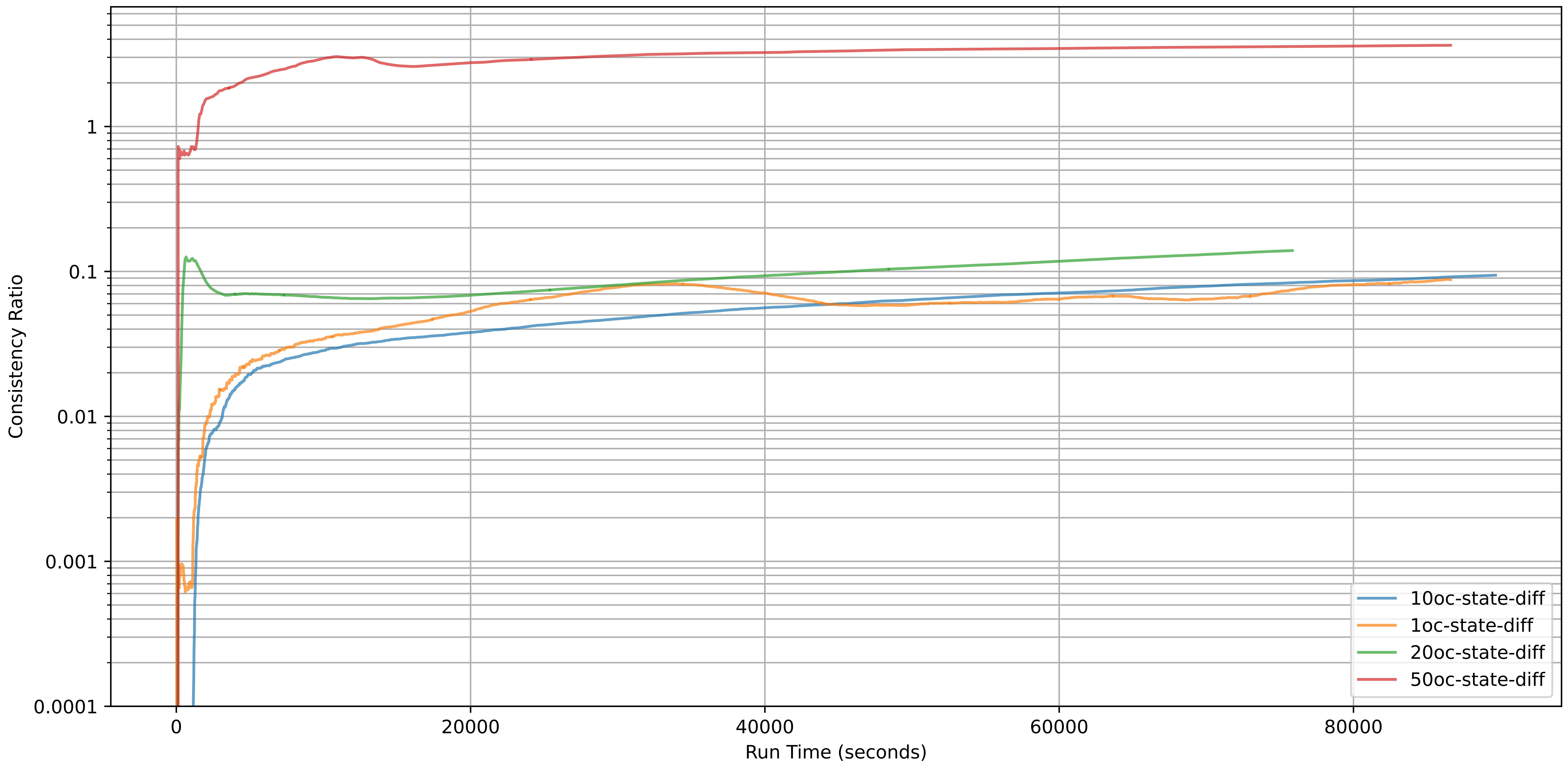


Overcommit



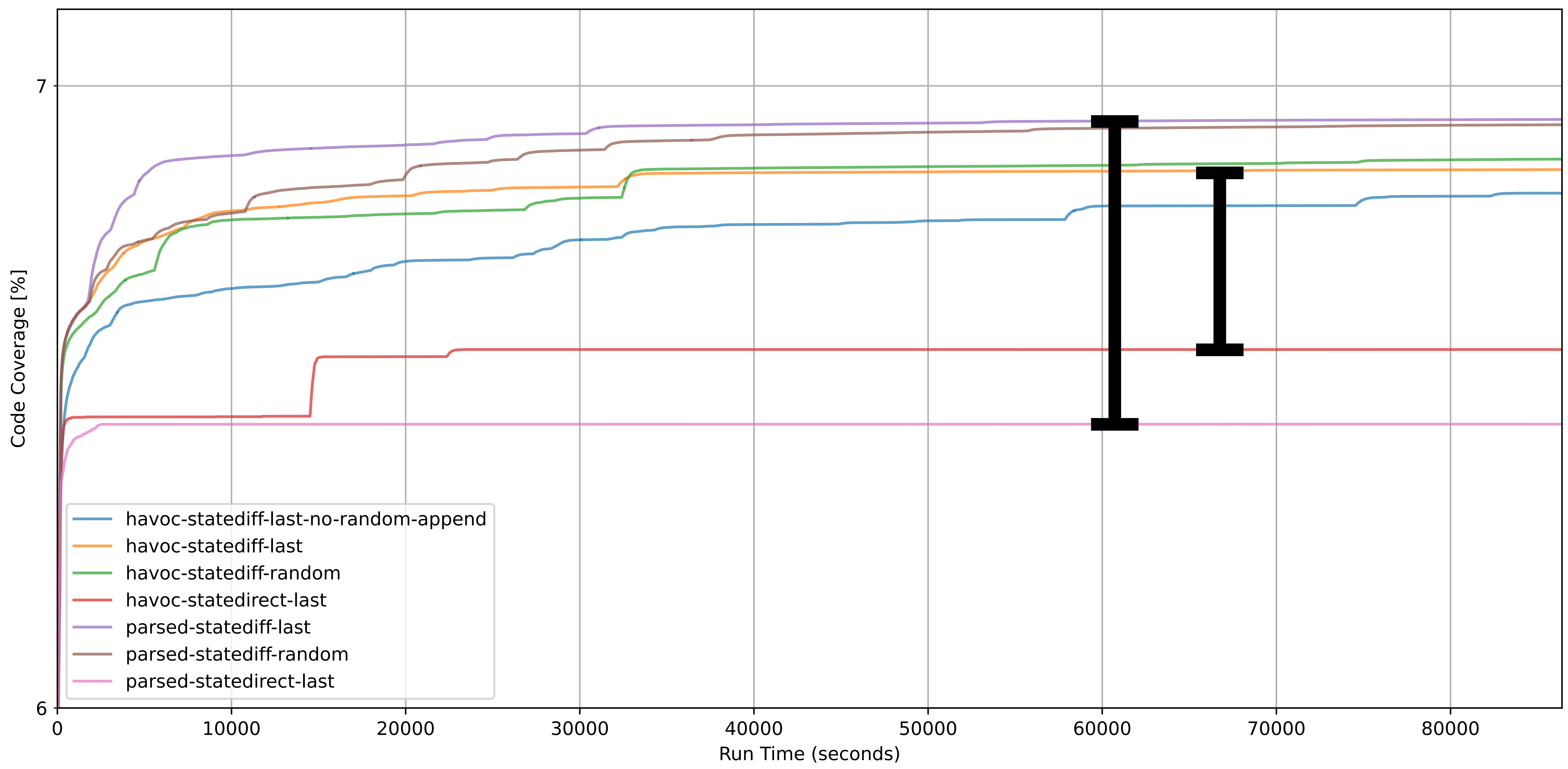
1000
100
10
1
Execution Speed (executions/s)
0
20000
40000
60000
80000
Run Time (seconds)
10oc-state-diff
1oc-state-diff
20oc-state-diff
50oc-state-diff

Overcommit

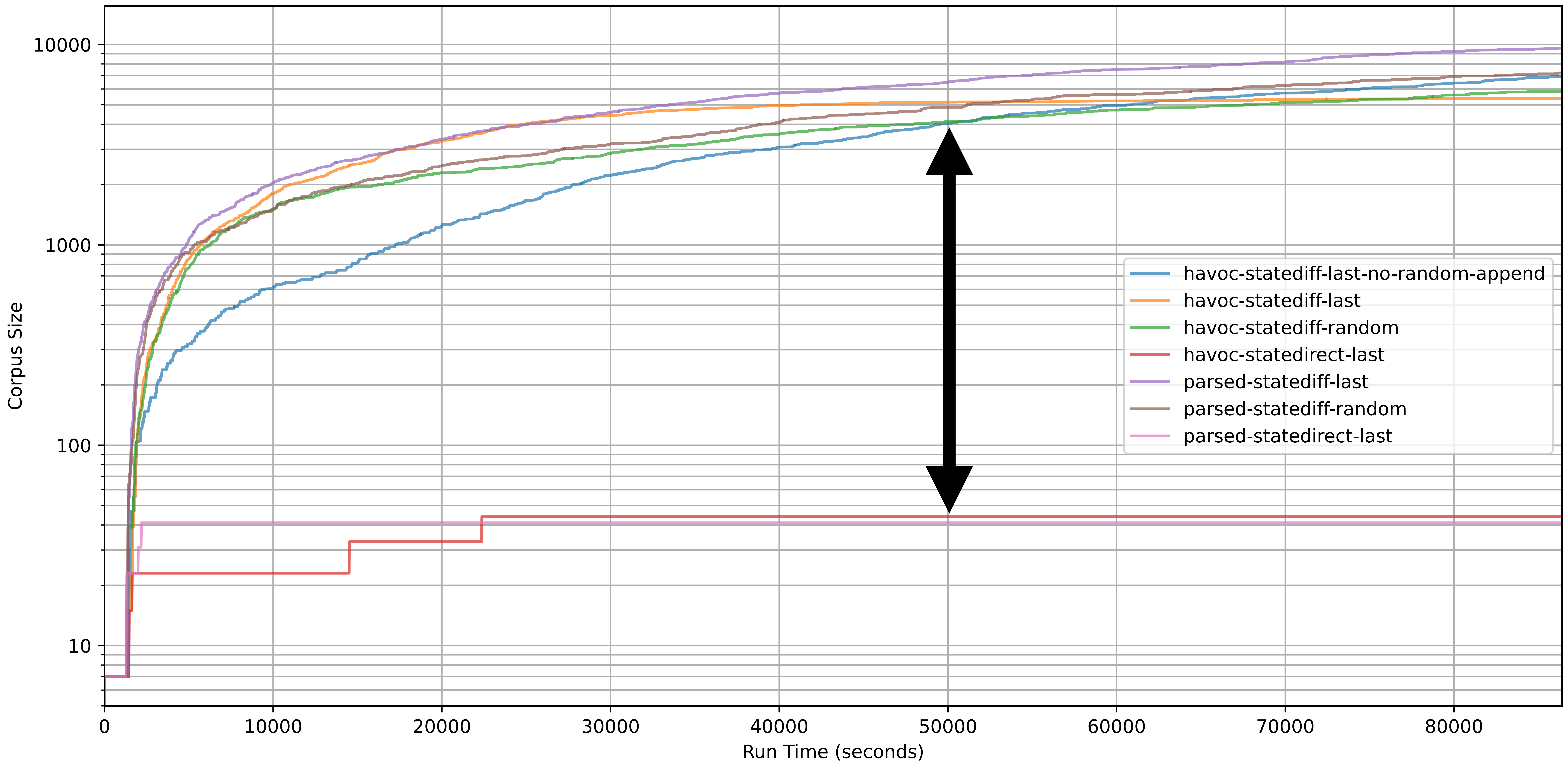


Consistency Ratio
1
0.1
0.01
0.001
0.0001
0
20000
40000
60000
80000
Run Time (seconds)
10oc-state-diff
1oc-state-diff
20oc-state-diff
50oc-state-diff

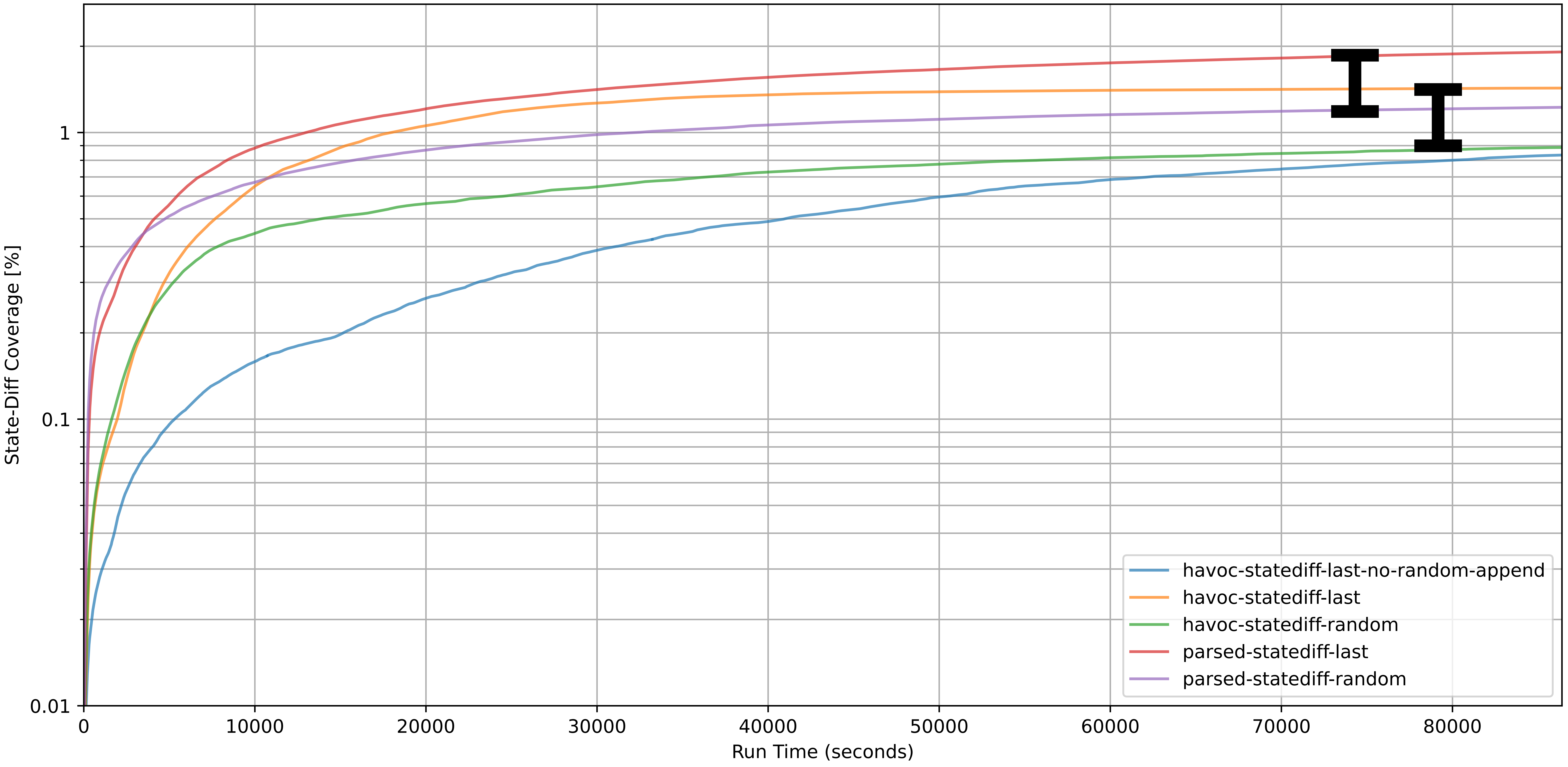
Evaluating Input Modeling and State-Inference Feedback

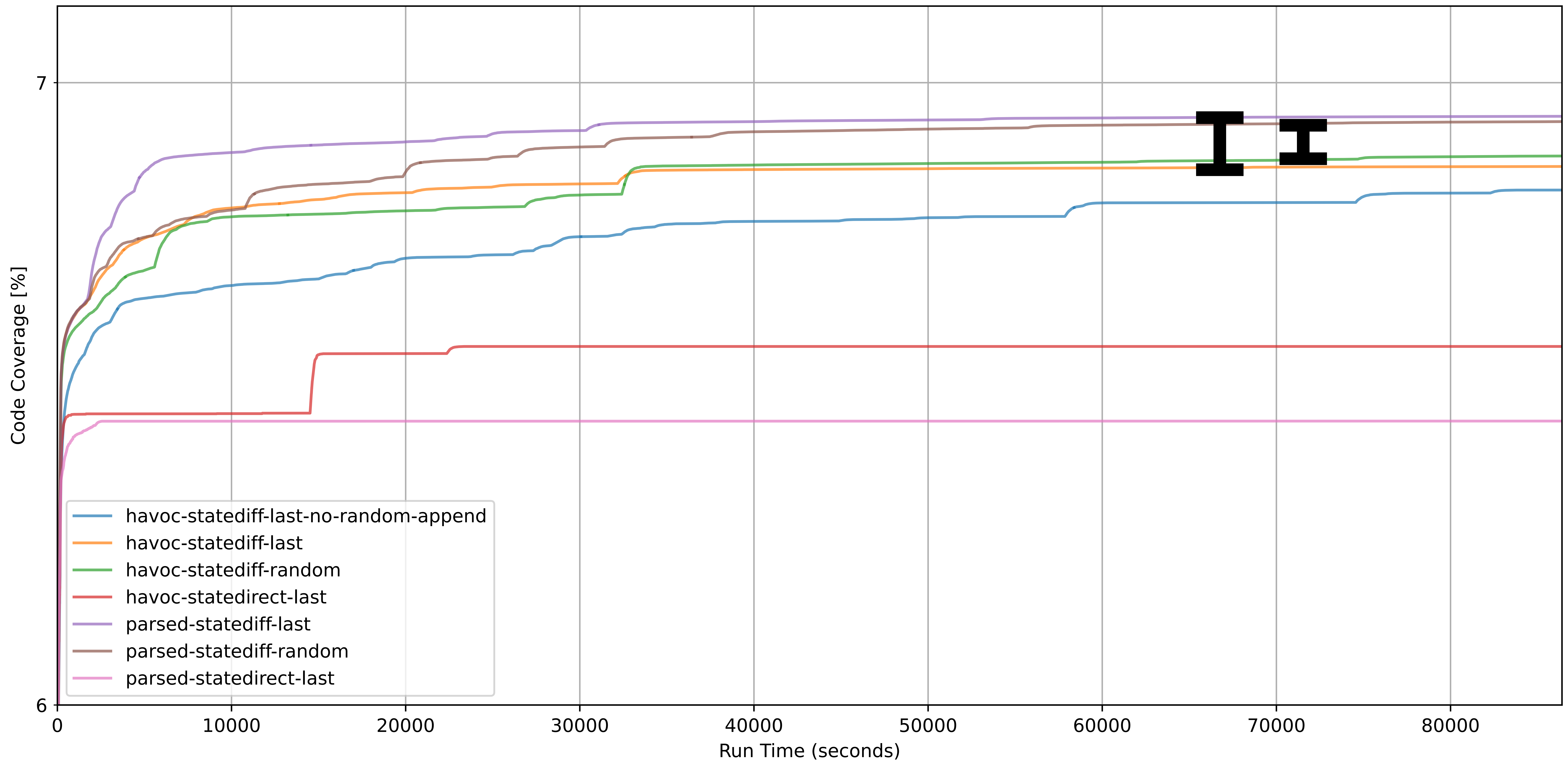


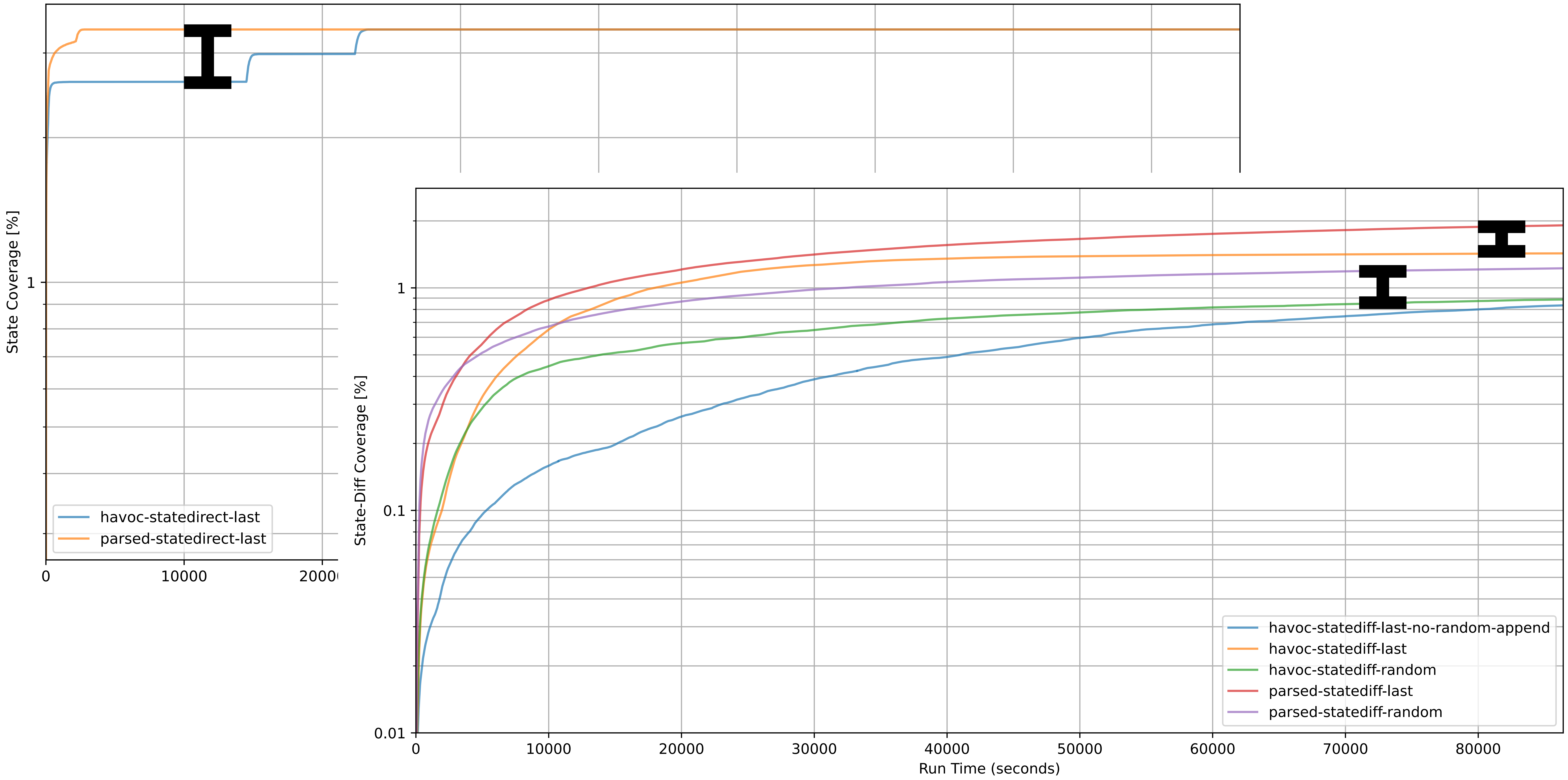
Code Coverage [%]
7
6
0
10000
20000
30000
40000
50000
60000
70000
80000
Run Time (seconds)
havoc-statediff-last-no-random-append
havoc-statediff-last
havoc-statediff-random
havoc-statedirect-last
parsed-statediff-last
parsed-statediff-random
parsed-statedirect-last

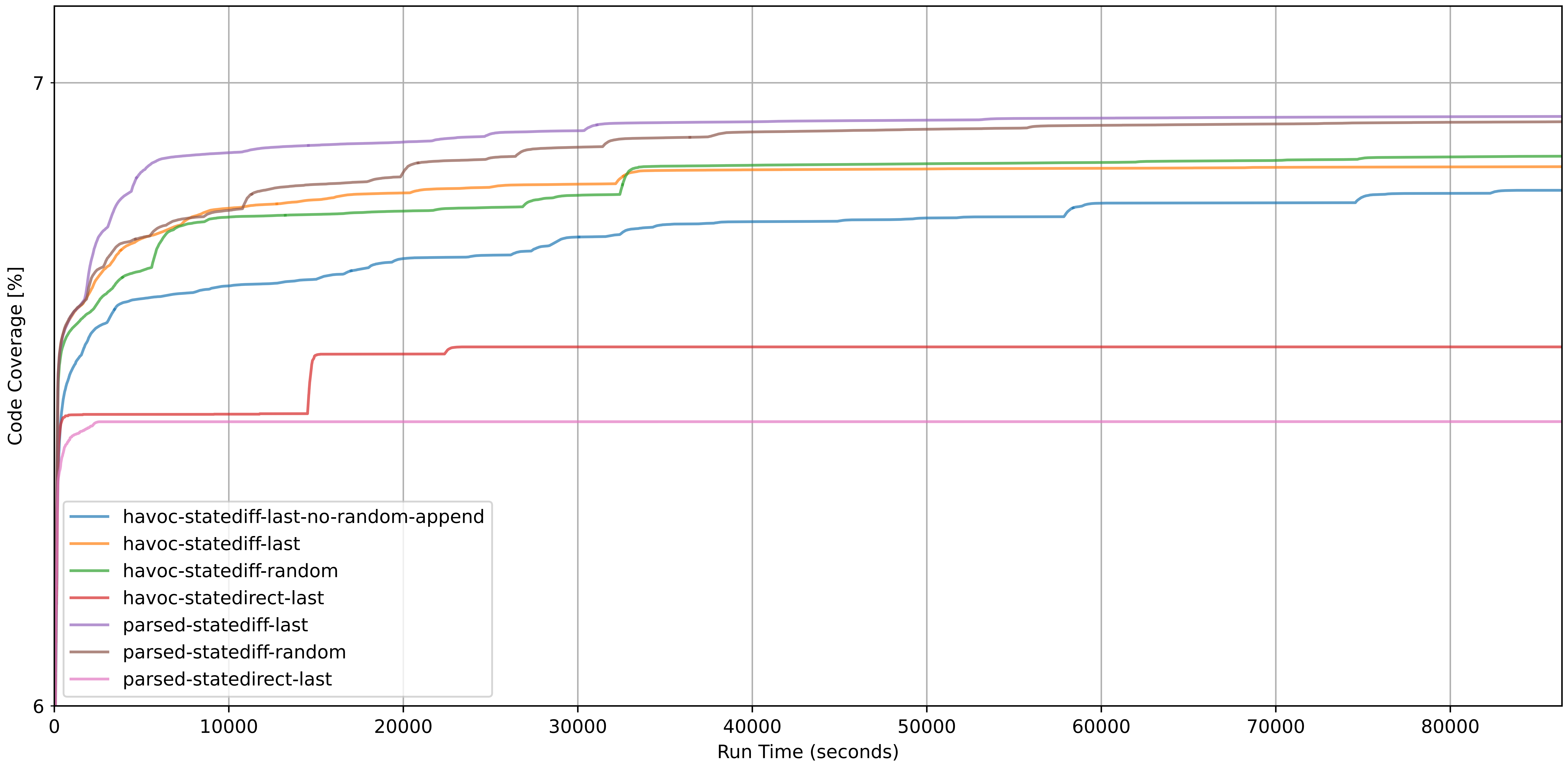

Corpus Size
10000
1000
100
10
0
10000
20000
30000
40000
50000
60000
70000
80000
Run Time (seconds)
havoc-statediff-last-no-random-append
havoc-statediff-last
havoc-statediff-random
havoc-statedirect-last
parsed-statediff-last
parsed-statediff-random
parsed-statedirect-last

Code Coverage [%]
7
6
Run Time (seconds)
0
10000
20000
30000
40000
50000
60000
70000
80000
havoc-statediff-last-no-random-append
havoc-statediff-last
havoc-statediff-random
havoc-statedirect-last
parsed-statediff-last
parsed-statediff-random
parsed-statedirect-last


State-Diff Coverage [%]
1
0.1
0.01
0
10000
20000
30000
40000
50000
60000
70000
80000
Run Time (seconds)
havoc-statediff-last-no-random-append
havoc-statediff-last
havoc-statediff-random
parsed-statediff-last
parsed-statediff-random


Code Coverage [%]
Run Time (seconds)
7
6
0
10000
20000
30000
40000
50000
60000
70000
80000
havoc-statediff-last-no-random-append
havoc-statediff-last
havoc-statediff-random
havoc-statedirect-last
parsed-statediff-last
parsed-statediff-random
parsed-statedirect-last


State Coverage [%]
1
0
10000
2000
havoc-statedirect-last
parsed-statedirect-last
State-Diff Coverage [%]
1
0.1
0.01
0
10000
20000
30000
40000
50000
60000
70000
80000
Run Time (seconds)
havoc-statediff-last-no-random-append
havoc-statediff-last
havoc-statediff-random
parsed-statediff-last
parsed-statediff-random



7
6
0
10000
20000
30000
40000
50000
60000
70000
80000
Run Time (seconds)
Code Coverage [%]
havoc-statediff-last-no-random-append
havoc-statediff-last
havoc-statediff-random
havoc-statedirect-last
parsed-statediff-last
parsed-statediff-random
parsed-statedirect-last

Conclusion

Future Work

- Instability
- Additional Parts of Zephyr
- Additional Targets
- Comparison to Other Fuzzers
- State-Inference Heuristic vs. Instrumented State Feedback
- Other Uses for State Feedback

FTZ: A State-Inferring Fuzzer for the TCP/IP Stack of Zephyr

- Efficient Execution and Interaction
- Improvements for Dealing With and Evaluation of Inconsistent Behaviour
- Evaluation of Different Message Modeling and Mutation Approaches
- Evaluation of Different Mutation Targeting Strategies
- Evaluation of State-Inference Feedback
- Contributions to Various Open-Source Projects

github.com/riesentoaster/FTZ

Seeding