

FTZ: A Stateful Fuzzer for the TCP/IP Stack of Zephyr

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Abstract

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Keywords: Software Testing, Fuzzing, Protocol Fuzzing, Stateful Fuzzing, Zephyr, LibAFL.

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1 Introduction

Zephyr is an open-source real-time operating system (OS) hosted by the Linux Foundation [1]. Real-time OSs allow programmers to define time constraints on their code, which are then guaranteed by the process scheduler. This is particularly important for safety-critical systems where delays in computation can pose serious risk, such as control of a robot. To achieve this, all operations have to be verifiably complete within a constant maximal time or fail safely. [2]. Zephyr is used in a wide range of products, including large industrial equipments such as wind turbines, medtech devices such as hearing aids, laptops controllers, or embedded devices such as emergency water detectors [3].

Zephyr projects typically connect to other devices or the internet using one of the OS’s networking libraries, such as the Zephyr TCP/IP stack. Since many of these devices need access to the internet, any defect in the network stack is comparatively likely to be remotely exploitable and thus critical. In combination with the potentially dangerous devices Zephyr runs on, this makes the correctness of these parts of Zephyr arguably important.

Fuzzing has been established as a widely used technique [4] to find software defects by repeatedly running a certain program under test (PUT) with a wide range of inputs and observing the execution for illegal program states such as crashes. It has been applied to great effect: Microsoft requires dominant software to be fuzzed prior to release [4], and its fuzzer SAGE [5] “reportedly found a third of the Windows 7 bugs between 2007-2009” [6]. Google mentioned finding 20,000 vulnerabilities in Chrome alone using fuzz testing [4], while its OSS-Fuzz program continuously fuzzing open-source software has resulted in over 6,500 vulnerabilities and 21,000 functional bugs fixed across 500 projects deemed critical enough to be included in OSS-Fuzz [7].

Ever since its inception in the nominal work by Miller *et al.* [8], who used random data to test Unix utilities, many improvements to fuzzing have been introduced to the state of the art. Among many others (Google Scholar retrieves more than 60,000 results in a search for “fuzz testing” [9]) include observing the program execution to guide the fuzzer when selecting the next input to test, or improved oracles such as memory sanitizers. Section 2.1 provides additional background on specific fuzzing technique employed in this project called mutational fuzzing.

However, fuzzing the network stack of an operating system poses three additional challenges: (1) they are deeply integrated with the OS, (2) they require

highly structured input data, and (3) they have internal state. These challenges are further elaborated in Section 2.2.

For this thesis, I developed a proof-of-concept Fuzzer targeting the TCP/IP stack of Zephyr (FTZ), built on top of the fuzzing library LibAFL. FTZ uses two different input representation along with appropriate mutation techniques, two strategies for targeting input parts to mutate, stateful feedback based on a heuristic requiring no target instrumentation, and reliability-enhancing logic to effectively test Zephyr. The remainder of this thesis is structured as follows:

- Section 2 presents further background on fuzzing in general and targeting TCP/IP systems in particular,
- Section 3 explores related works,
- Section 4 explains the different techniques used in FTZ, along with how they were implemented,
- Section 5 presents and discusses the results achieved in the evaluation of FTZ,
- Section 6 summarizes the findings of this thesis.

2 Background

This section presents additional background information required to understand the remainder of this thesis.

2.1 Mutational Fuzzing

FTZ implements mutational fuzzing. This is a technique use across a wide range of influential fuzzers, such as AFL++ [10], syskaller [11], libFuzzer [12], Honggfuzz [13], or OSS-Fuzz [14]. A mutational fuzzer maintains a corpus of inputs, first seeded at startup with a number of entries that are either generated randomly or loaded from a predefined set. The fuzzer then iteratively chooses one of the inputs in its corpus, mutates it in some way, and evaluates it in the PUT [15].

During the execution, mutational fuzzers observe the PUT in certain ways, such as by collecting information about which parts of the PUT’s code were executed. These fuzzers are also known as greybox fuzzers — a mixture between blackbox fuzzers, which do not know anything about the internals of the PUT during the execution, and whitebox fuzzers, which further analyze the executed logic using symbolic execution or taint analysis [4].

The data observed during target execution is then used to decide if the current input should be added

back into the corpus. The most common form of such feedback is coverage-guided fuzzing, which adds an input to the corpus if new coverage was measured in the PUT. This incentivizes the fuzzer to explore previously untested parts of the PUT [10].

2.2 Fuzzing Network Stacks Is Hard

As introduced in Section 1, fuzzing an operating system’s network stack introduces three additional challenges.

2.2.1 Deep integration with OS

OS’ built-in network stacks are deeply integrated with other subsystems, such as the memory management subsystem for accessing the network interface card and socket buffers, or the system’s scheduler for event notifications. Extracting the network stack from the rest of the kernel to be run independently is therefore infeasible, since it would require extensive additional engineering, which is error-prone and may result in findings that do not hold on the original implementation [16].

To test the network stack of an operating system using a fuzzer, one therefore has to run the entire operating system, which includes a lot of logic unrelated to the network stack itself, thus introducing a significant performance penalty. This further means that any sanitizer has to be introduced into the OS’ build system, which may not be possible because the additional logic may break assumptions made by the OS developers (see Section 4.1). Finally, OS’ kernels are by definition tightly integrated with hardware, and running an operating system therefore requires either dedicated hardware (which may be hard to observe and communicate with), or some form of hardware and environment simulation, introducing additional performance penalties.

2.2.2 Network Packets Are Highly Structured

Table 1 shows the structure of a packet, as it would be used to seed FTZ’s corpus with. Many of the fields across all layers depend on values of other fields in their own or even other layers. Examples of these include length fields marked with green or checksums marked with blue. Checksums such as the CRC32 frame check sequence in the ethernet trailer or the 16-bit one’s complement-based checksums in the IPv4 and TCP headers are a prime example of logic fuzzers struggle to penetrate. This is because mutating one part of the data requires very specific changes to another, which is highly unlikely to happen in random

mutation [17]. This challenge has garnered some attention from previous work, such as removing the program sections responsible for checking checksums from the target program [18], or bypassing them [19].

The sequence and acknowledgment numbers in the TCP header are dependent not only on the current packet, but on previously sent packets. Similarly, the TCP header flags have different meaning depending on the state of the recipient’s TCP stack.

2.2.3 TCP Stacks Have Internal State

The fact that TCP is a stateful protocol increases the state space to be explored by the fuzzer dramatically, and the fuzzer may find it hard to reach ‘deeper’ states [20]. Indeed, stateful targets are listed among the remaining challenges in fuzzing by Boehme *et al.* in their review paper [21]. Ba *et al.* demonstrate that simply relying on coverage information is insufficient to fully test stateful code, but the state of the target has to be taken into account [22]. A similar conclusion was drawn during the evaluation of StateFuzz [23].

TCP being a stateful protocol introduces two fundamental challenges to the architecture of the fuzzer:

1. To retain the ability to triage the software error found by the fuzzer, one needs the ability to repeatedly cause the same error. Since the PUT may be put into different states with each message, this means all previous interaction with a PUT instance need to be recorded, records which may grow increasingly large across a fuzzing campaign with billions of executions and even more packets exchanged. Additionally, even recordings across long interaction chains may not suffice if the target does not always behave predictably. To mitigate this challenge, FTZ restarts Zephyr before each trace evaluation, trading off the additional runtime for increased simplicity and reliability, and reduced memory and storage consumption.
2. The trace to be mutated needs to contain all previous interaction with the PUT, which put it into a certain state, in addition to the last packet the fuzzer attempts to trigger an error with. Section 4.4 presents different approaches evaluated in this project.

Daniele *et al.* introduce a taxonomy of stateful fuzzing in which they define a stateful system as “a system that takes a sequence of messages as input, producing outputs along the way, and where each input may result in an internal state change” [20]. TCP stacks are such a stateful system. This thesis will follow the naming convention outlined in their same

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

Table 1: Structure of a network package as used during seeding of FTZ. Gray fields are optional, green fields length-dependent, and blue fields checksums.

work, reserving “the term message or input message for the individual input that the System Under Test (SUT) consumes at each step and the term trace for a sequence of such messages that make up the entire input.” [20]

2.3 LibAFL

LibAFL is a fuzzing library written in Rust by the maintainers of AFL++. They have observed how many different fuzzers implement similar patterns and data structures, or even fork an existing fuzzer, but only change one specific part of the fuzzer. However, their improvements rarely get implemented in the upstream fuzzer. This leaves the fuzzing community with a list of provably effective algorithms implemented in incompatible projects. LibAFL provides generic interfaces for common functionality such as schedulers or mutators and default basic default implementation of each. Additionally, many advanced algorithms such as the mutation scheduler from MOpt [24], the weighted input scheduler from AFL++ [10], Hitcount coverage postprocessing from AFL [25], or execution-dependent mutation from REDQUEEN [19] have been added. In Nov. 2022, when LibAFL was released, improvements from 20 prior works were implemented and evaluated individually and in combination. Since then, additional algorithms and improvements have been introduced to make LibAFL a powerful and flexible base for FTZ. Section 4 presents the details of how LibAFL is used in FTZ [26].

3 Related Works

3.1 Fuzzing Zephyr

I was unable to find scientific work evaluating fuzz testing on Zephyr. **2.Check again** There are however reports of fuzzing campaigns available, listed and compared to FTZ here:

Zephyr has an integration to test parts of the software that are callable from user code using libFuzzer. Compilation of an instrumented version of the OS and linking with libFuzzer is possible with a simple build system configuration entry. However, the example project used as an explanation in Zephyr’s documentation does not contain any kernel logic and instead dummy code showing the abilities of coverage-guided fuzzing [27], [28].

There is also an adaption of this example that allows using FuzzBuzz as the fuzzer backing the execution instead of libFuzzer [29].

According to [30], the libFuzzer integration has successfully been used to test Zephyr’s bluetooth stack. While the blog post mentioning the campaign claims that it helped finding several bugs, it does not provide any detail about the campaign, employed techniques, or evaluation. Besides targeting a different part of Zephyr, it uses libFuzzer, which is a pure coverage-guided fuzzer without any state feedback, so this campaign likely did not use state feedback.

The blog post further describes using the Renode hardware systems simulator in combination with AFL [25] and AFL++ [10] to fuzz Zephyr, specifically the `console/echo` sample. An artificial bug is introduced into the sample code, which will result in a segmentation fault if a certain character is passed to Zephyr. Renode hooks are used to pass data to Zephyr through an emulated UART interface. Custom scripts are required to facilitate the communication between AFL++, Renode, and Zephyr. The setup described in this blogpost describes the alternative way of fuzzing compared to FTZ: emulation. Section 4.1 provides the reasoning behind FTZ’s different approach. Compared to FTZ, AFL and AFL++, as used in this project, only support coverage feedback as opposed to FTZ’s state feedback [30].

Finally, Oka and Makila discuss fuzzing Zephyr projects in a continuous integration environment. However, their work is not publicly accessible and the available information about their work does not provide information about technical details of their approach [31].

3.2 Stateful Protocol Fuzzing

The wider field of protocol fuzzing has received considerable attention. A set of works published before October of 2024 have been selected to represent the potential improvements implemented and evaluated in FTZ. Stateful protocol fuzzing has received considerable attention — refer to the survey papers such as [20], [32], [33] for a more complete overview over the state of the art.

Natella and Pham propose a benchmark for stateful protocol fuzzers in ProFuzzBench [34], containing a suite of 10 protocols and 11 open-source implementations of those to be tested. TCP notably is not part of this benchmark directly, but is used as an underlying protocol for others, such as FTP. State feedback is provided by HTTP status codes — certain protocols such as FTP already provide these, others are patched to do so based on a superficial heuristic for their state. The authors note that configuration of the targets is not taken into account and multi-party (≥ 3 participants) protocols cannot currently be fuzzed. Non-

determinism in the programs make feedback (like code coverage) less predictable and thus fuzzing less performant, because it introduces non-differentiable duplicate entries into the corpus.

However, of the fuzzers projects discussed in this thesis, only StateAFL [35] is evaluated against this benchmark, while EPF [36] notes the absence of such a benchmark for their work.

3.2.1 Observing State

As described in Section 2.2.3, a key challenge in fuzzing implementations of participants to stateful protocols is providing information about this state back to the fuzzer to then be used. Extracting this information from a PUT has been achieved using various techniques across projects:

Manual Annotation Ijon [37] is an extension to AFL and requires analysts to manually annotate the PUT’s code. Ijon introduces logic at the annotated location to add entries to an AFL-style map, in either a tainting or counting mode. It can further directly include state information such as variable values in how the edge coverage is calculated, and store the maximum value a certain variable reaches during execution for the fuzzer to then maximize back in the fuzzer. However, the only target Ijon is evaluated on and resembling a protocol is the CROMU.00020 target of the Darpa Cyber Grand Challenge, which requires inferring the state of the target to successfully trigger the error. There, Ijon showed improved performance compared to unmodified AFL.

Automatic Annotation Manual annotations of state variables is tedious, error-prone, and requires a decent understanding of the PUT internal structure by the analyst. Because of this, many projects attempt to use a heuristic to automatically find variable or memory locations representing the current state of the PUT and passing this information back to the fuzzer.

Ba *et al.* rely on the intuition that variables representing the state of their target are often assigned from named constants in an enum struct. At all locations updating these variables, instrumentation is injected to pass the information back to the fuzzer [22].

SandPuppy [38] performs an initial run of the PUT, capturing variable-value traces, and uses a heuristic based on this information and static analysis of the source code of the PUT to identify state-representing variables. These are then instrumented with a Ijon-like feedback mechanism. This process is

repeated at certain intervals during the fuzzing campaign. Compared to Ijon, minor improvements were achieved, such as additional solved Super Mario Bros levels. It further shows that state feedback generally improves achieved coverage compared to pure coverage-guided fuzzers such as AFL, AFL++, or REDQUEEN, and even compared to the heuristic to identify state-representing variables in SGFuzz.

StateFuzz [23] identifies state-representing memory by looking for variables that are long-lived, updatable by the user, and either change the control flow or are used to index into memory. StateFuzz identified a four digit number of state variables in the Linux and Qualcomm MSM kernel used in Google’s Pixel line of smartphone.

Other Greybox Heuristics StateAFL [35] relies on compile-time probes observing memory allocation and I/O operations to identify state-representing memory locations. State inference is then done based on fuzzy hashing of long-lived memory areas. Their approach proves effective, even compared to other state-aware fuzzers such as AFLNet.

TCP-Fuzz [39] and Ankou [40] take the combination of executed branches as a heuristic for the state of the target. Because this approach leads to a number of states much larger than the states of the abstract state machine powering the server (TCP-Fuzz found 47.9K state transitions in the TCP stack mTCP), Ankou further reduces this complexity for a custom adaptive fitness function.

3.2.2 Use of State Information

The state information extracted or inferred using these techniques is then passed to the fuzzer, which uses it in different ways.

Feedback In mutational fuzzers, state information can be used in several ways to decide whether an input should be considered interesting and thus added to the corpus. Examples of this includes StateFuzz [23], which considers inputs interesting that trigger additional, previously unchanged states, state values representing a new value range, or new extreme values. Value ranges are binned values of states determined to be congruent using symbolic execution. AFLNet [41] allows users to specify that not only states but also state-transitions should be used to determine the interestingness of an input. DDFuzz [42] uses a similar approach, but does not directly rely on state information and instead uses execution of new inter-data dependency relationships as feedback.

Scheduling The state of the PUT as observed using any of the methods described above can then be used to improve both input and mutator scheduling, as shown by the following approaches:

Several projects create an abstract data structure representing the state space and possible state transitions of the PUT. This can then be used to improve scheduling. Examples include ZFuzz, which calculates an ad-hoc directed graph based on measured states, while SGFuzz [22] constructs a similar data structure called a state transition tree. Finite state machines are a popular structure to model state transitions, as implemented by Jero *et al.*, whose fuzzer requires manual specification of the FSM based on the protocol specification, or Hsu *et al.* [44], who additionally implement FSM minimization. Autofuzz [45] on the other hand employs a bioinformatics algorithm to approximate the FSM.

These structures are then used in several ways: AFLNet [41] uses a custom heuristic based on statistics about each state to schedule the next input to be mutated. SGFuzz [22] guides the fuzzer to under-explored parts of the state-space by scheduling input traces leaving the PUT in such a state for the next mutation. The structure can further be used to schedule which mutator(s) should be invoked next [44]. ZFuzz [46] does this based on a formula incorporating state depth, coverage, number of transitions, and number of mutations based on this state.

3.2.3 Target Differences

While all of the projects presented above introduce provably effective approaches to increase a fuzzer’s performance on their targets by using state feedback, only TCP-Fuzz [39] has the same target as FTZ: TCP/IP stacks.

Others target BitTorrent [40], DNS [35], FTP [35], [41], [45]–[47], HTTP2 [22], Modbus-TCP [48]–[53], MSNIM [44], RTSP and other media streaming protocols [22], [41], SMTP [35], SSH [35], or SSL/TLS [22], [42], [46] libraries, or SCADA systems [36]. TCP/IP is used by some of these fuzzers to facilitate communication between the fuzzer and PUT, but not evaluated independently or declared as out-of-scope. To compare the effectiveness of improvements introduced by a certain fuzzer, some are further evaluated against mazes [37], [38], levels of the game Super Mario Bros [37], [38], or file formats with complex data-interdependencies [37], [38], [40], [42].

Thus, comparisons are impossible without reimplementing the logic of either related work for FTZ’s targets, or the other way around. Additionally, such changes to related works would also need to include

the custom logic to exchange packets with the PUT introduced in FTZ — this also applies to TCP-Fuzz.

3.3 Input Modelling and Targeted Specific Mutation

Section 2.2.2 introduced how mutation on inputs that have high data interdependence such as length fields or checksums is one of the core challenges for mutational fuzzers targeting logic processing such inputs. While most protocol fuzzers rely on random mutation, certain works have proposed improvements to better mitigate this issue.

EPF [36] uses population-based simulated annealing to schedule which packet type to add or mutate next in conjunction with coverage feedback. It requires Scapy-compatible implementation of packet types to be fuzzed to ensure packet structure. TCP-Fuzz models the inputs to the TCP/IP stacks tested as a list of system calls and packets, and mutates these lists while ensuring certain constraints between input parts, such as `socket`, `bind`, `listen` and `accept` being always called in order if a connection is in a certain state. However, TCP-Fuzz randomly selects which part of the input is mutated next. Since FTZ employs a similar technique, it includes the major downside of this approach: the structure of the packets and constraints to be ensured after mutation have to be specified manually.

Alternatively, approaches such as MTA [51], GAN-Fuzz [50] or Autofuzz [45] attempt to automatically learn the structure of the inputs based on generative adversarial networks [50], simplified transformers [51], or bioinformatics techniques [45].

3.4 Machine-in-the-Middle

As opposed to other works, FitM [47] and Autofuzz [45] attempt to fuzz both the server and client implementations of a protocol library through machine-in-the-middle mutation. The former uses userspace snapshots of the entire client and server processes instead of a log of previous messages (see Section 2.2.3), while the latter constructs a finite state automaton from the observed packets to intelligently mutate messages.

4 Implementation

This section describes the architecture and implementation details of FTZ. It relies on Zephyr’s `sockets/echo` sample, a simple example implementing a TCP/IP server that echos any data back to the client.

4.1 native_sim

During the compilation of Zephyr, a target board has to be set. One such target provided by the Zephyr project is called `native_sim`, with which the entire operating system and all user code can be compiled into a Linux executable based on a POSIX architecture. It is based on NativeSimulator, and provides a wrapper around Zephyr with a main function, a scheduler mapping from the host’s scheduler to Zephyr’s scheduler, hardware models, interrupt controllers, and basic CPU functionality like threading and start/sleep/interrupt calls [54]. Its integration with Zephyr provides certain functionality to use the host operating system’s functionality such as ethernet, UART, or display drivers, among others [55].

The ability to run Zephyr as a native executable allows the use of native debugging tools such as `gdb` and makes computationally expensive translation layers such as QEMU unnecessary, thus increasing the efficiency of the target. This is especially relevant for a fuzzer since it runs the target millions of times.

When targeting `native_sim`, Zephyr’s build system can further be instructed to compile the code using AddressSanitizer (ASAN). This compiler pass instruments the target binary with additional runtime checks for memory errors such as out-of-bounds accesses to heap, stack, or global variables, use-after-free and use-after-return errors, or double frees [56]. Both the default toolchain based on `gcc` and the alternate LLVM/`clang`-based toolchain provide such instrumentation.

During this project, I discovered a bug in Zephyr’s device registration when using the ASAN implementation of `clang`, which I needed to use for its superior coverage instrumentation (see Section 4.2). I worked together with the maintainers of Zephyr to triage and fix this bug [57].

`native_sim` allows manipulating the clock of Zephyr, to run the operating system faster or slower than realtime, or disabling any speed restrictions. The latter however renders any `sleep`-interrupted loop into one that runs nearly unrestrictedly fast. This in turn leads to near-instant timeouts of connections and is thus unsuitable for interaction with an other system such as the fuzzer. However, passing `--rt-ratio=<n>` to the executable built with the target `native_sim` allows a user to set the ratio of how quickly Zephyr’s virtual time passes compared to real-time.

4.2 Coverage Information

To guide the fuzzer and measure its progress, FTZ measures the executed code under each trace (re-

```

1 void __sanitizer_cov_trace_pc_guard_init (
2     uint32_t *start,
3     uint32_t *stop
4 ) {
5     for (uint32_t *x = start; x < stop; x++) {
6         *x = 0;
7     }
8 }
9 void __sanitizer_cov_trace_pc_guard (
10    uint32_t *guard
11 ) {
12     *guard += 1;
13 }

```

Listing 1: SanitizerCoverage Hook Implementations

fer to Section 2.1 for more details on coverage feedback). A method commonly used and well-supported by LibAFL to do this is using `clang`'s SanitizerCoverage compiler pass. It instruments the code with two functions, as shown in Listing 1.

The first is called at program startup and allows initializing a memory section (delimited with `start` and `stop`). The second is called on each basic block edge, with a guard unique to this edge, pointing in the previously initialized memory section. The implementation above counts how often every edge is executed.

Initial measurements suggested that the coverage measured when running Zephyr using the `native_sim` wrapper is inconsistent (see Section 5.1), particularly in the code sections responsible for matching host thread to Zephyr thread, the execution of which depends on the (unpredictable) host scheduler. Thus, an alternate implementation of `__sanitizer_cov_trace_pc_guard` is used in FTZ, which only marks the visited edges as executed, instead of counting the executions, to stabilize the results.

To prevent additional instability, I reduced the changes to existing logic in both the code and build system to a minimum. To achieve this, my implementations for the SanitizerCoverage functions are in a separate module, which is included in the build system. For this, a single entry is added to the appropriate CMake file and a single option is added to Zephyr's configuration system.

To increase performance and be more error-resistant, the coverage is directly written into shared memory created by the fuzzer. During the initialization, the shared memory is opened based on information passed through environment variables. Additionally, the information needed to map from the SanitizerCoverage-reserved memory section to the shared memory section is stored. On each edge, the

appropriate address in the shared memory section is calculated and marked as visited. While there is a slight performance-penalty on each edge due to the address mapping, this approach does not require any post-processing on the client's part, such as copying the collected information back to the fuzzer. This is particularly important in cases of crashes in the PUT, since any post-processing function would no longer be called.

4.3 Exchanging Network Packets with Zephyr

Zephyr's `native_sim` already provides an ethernet driver for a TAP interface over a zeth interface [55]. However, for this project, I opted to build an alternative solution to circumvent the additional limitations of the host kernel interaction. Instead, I built a custom ethernet driver based that transmits network packets between the fuzzer and target using shared memory.

As described above, I again wanted to limit the required changes to existing logic as much as possible. To achieve this, the configuration system is extended with an alternative to the existing TAP-based ethernet driver. The new configuration is then used in the appropriate CMake files to include the logic for the shared memory-based ethernet driver. Similar to the existing TAP-based driver, the logic is split into a part compiled into the kernel directly, and one for all interaction with the host system.

The driver requires a single shared memory segment, the information of which is passed to the PUT using environment variables. There, it is initialized in the driver initialization hook provided by Zephyr. The memory section is split into four parts: one buffer and status field each for each direction. The status field is set to a negative number as long as the buffer is empty, and set to the length of the packet when a packet is sent in either direction. Zephyr's TAP-based driver utilizes sleep-interrupted polling of the network, and so does the shared memory-based implementation.

Initial experiments showed that certain packets are received at unpredictable intervals or need to be consistently sent to access the TCP logic. The responses to these interactions are manually constructed in the fuzzer and sent to Zephyr. Currently, FTZ manually responds to ICMPv6 packets of type NeighborSolicit and RouterSolicit, and to ARP requests for the fuzzer's MAC address.

4.4 Input Modelling and Mutation

Section 2.2 introduced multiple challenges in fuzzing network stacks in general, and TCP stacks specifically. FTZ implements multiple approaches to mitigate some of those challenges, the details of which are discussed here.

4.4.1 Trace Modelling and Mutation Target

AFLNet [41] and TCP-Fuzz [39] select a random message from the trace to mutate. However, this strategy has one significant intuitive drawback: If the corpus contains a long trace generated across many executions to arrive in a specific state by combining a large number of messages, and the mutation strategy chooses the first message to mutate, the remaining messages are likely going to be irrelevant, because the initial state changes.

Alternatively, one could approach this problem in a similar fashion to FitM [47]. Maier *et al.* essentially build a tree by snapshotting executions and only appending entries. This way, any state can still be reached, but it does not require the fuzzer to needlessly evaluate long traces.

In FTZ, I introduce `ListInput`. It contains a list of messages, and each entry can be mutated in two ways: Either, the trace is mutated by appending, removing or replacing a message, or individual messages are mutated. For the former category, FTZ is configured to append messages from either the recorded interaction or generated randomly. Mutators on individual messages can be configured using `ListInput::map_to_mutate_on_last` or `ListInput::map_to_mutate_on_random` to either target the last or a random message, representing the strategies in AFLNet and TCP-Fuzz, and FitM respectively.

4.4.2 Seeding

Since both options of modelling a trace include mutators appending messages to a trace, one could seed the corpus with a single, empty trace. In principle, the fuzzer will still eventually find its way through the entire state space. However, one can speed up this process greatly with an improved seeding strategy. For this, I first traced an entire full and legal interaction between a client and Zephyr. The trace is then filtered for TCP messages going from the client to the server. Then, the corpus is seeded with slices of this filtered list of messages, starting with the an empty trace and then including increasingly more consecutive messages, all starting with the first filtered message.

The fuzzer is forced to include *all* traces into its corpus. This is necessary as the server may not respond to every message with an answer, and two traces therefore may look the same to the fuzzer.

This improved seeding strategy does not diminish the state space the fuzzer is able to explore — the empty trace is still part of the corpus. But it provides the fuzzer with traces ending in many different legal states, thus negating the need for the fuzzer to find its way to deeper states by pure mutation.

4.4.3 Input Message Modelling and Mutation

Then, there is the question of how to model individual messages. Here, three fundamental approaches could be considered: (1) any representation and exclusive crossover mutations, (2) byte arrays and random mutation, (3) parsed structure with different levels of manual fixing of values after random mutation.

First, when one only allows crossover mutation of full messages, i.e. appending a message randomly drawn from any other entry in the corpus or a fixed list, how the input is modelled does not matter, since the messages themselves are never changes. However, this approach severely limits the kinds of traces a fuzzer is able to generate and thus unsuitable for general fuzzing.

Second, one could model a packet as a byte array and mutate it with the default `havoc_mutations` from AFL++ [10]. These include among others byte increments and decrements, bit flips, crossover copying or inserting of subsections of the byte array, setting a byte (combination) to a magic value known for triggering specific types of errors, or deleting parts of the byte array. However, as discussed in Section 2.2.2, TCP packets are highly structured and include various checksums. These are unlikely to be calculated correctly by random mutation and thus fuzzers relying on packets generated through `havoc_mutations` are not going to be able to explore past the server’s code past the initial parsing logic.

The last option includes modelling a packet as a data structure representing all parts of the raw packet, across all layers. These could then be mutated more selectively. Parts of the packet representing a number can be mutated with number-specific mutators (like setting them to interesting values), bit fields can be mutated as such, and one can fix magic values or checksums manually. This approach represents a tradeoff between the ability to generate a wide range of messages and thus traces, while keeping the generated messages reasonably valid as to not be outright rejected by the parser.

When employing the third option, one has fine con-

trol over what mutations are done by the fuzzer, and what data has to be set manually. One could even allow the fuzzer to mutate checksum or length fields and only overriding the mutated values to the correct ones selectively. This approach tests both all parts of the input parser and still is able to reach the business logic of the TCP stack.

The drawback of this last option is that it requires the analyst to specify the structure of the network packet. For common protocols such as TCP/IP, there are libraries available, which significantly reduce the required programming overhead, but one still needs to decide which parts of the message should be randomly mutated and which parts should be fixed. The engineering overhead when using LibAFL has been significantly reduced with `MappingMutators`, which are discussed in Section 4.7, along with other improvements to LibAFL implemented during this project.

4.5 State Inference Heuristic

Section 2.2.3 discussed how the internal state of the TCP stack is a major challenge for fuzzers. One promising response to mitigate this issue is adding state feedback to the fuzzer. This allows the fuzzer to take into consideration the differences in the state of the PUT’s TCP state machine when assessing whether a new trace is worth adding to the corpus.

To implement this, I mapped incoming messages to a state, represented by a number: Any valid TCP packet is mapped to the `u8` representation of its header flag, other packets are mapped to different states representing the alternate packet content (such as packets not containing layer 4 data), or the error source (such as packets with an invalid IP header).

These state numbers are then used to index into a memory slice representing the TCP state space, similar to how coverage is catalogued in a coverage map. Compared to coverage measurements, one needs to consider that simply counting how often each state is measured, incentives the fuzzer to produce increasingly long traces, even if no new actual state is reached. FTZ therefore only marks which states were measured at any point during evaluation of a trace. This further improves reliability, with a similar argument as is presented in Section 4.2.

Section 4.3 discussed that Zephyr emits certain ICMPv6 packets at unpredictable intervals. To optimize the reliability of state-based feedback, ICMPv6 packets are therefore not mapped to the state memory map.

Two ways of calculating state-feedback were implemented in FTZ:

1. Messages emitted from Zephyr are simply

mapped to states, and stored in the state memory map. This mode will be called state feedback.

2. Alternatively, the state transition is calculated from an incoming packet and the previous packet, to incentivize the fuzzer to explore all possible state transitions. To implement this, the fuzzer keeps track of previously sent and received messages — since state transitions depend on packets sent both from the client and the server, both directions are taken into account. On each incoming message, FTZ calculates a unique identifier for the measured state transition between the current and last packet, which is then used to index the state map. State transitions are only measured for each incoming message, because otherwise, when the fuzzer finds a way to send at least two arbitrary packets without a response, the entire state space would be accounted from fuzzer-emitted packets, while the TCP stack of Zephyr remains in the same state. Using the state transitions as feedback will be labeled as using state-diff feedback.

4.6 During an Execution: Implementation Details

This section describes the details of the implementation of the different parts of FTZ. For additional details refer to the architecture diagram of LibAFL in Figure 1 and their paper [26] for the interaction of the different structures.

4.6.1 Central Infrastructure

The fuzzer relies on `CentralizedLauncher` to spawn a number of clients, each with their own data structures and each spawning their own instance of Zephyr. `CentralizedLauncher` synchronizes inputs that were added to one of the client’s corpi to minimize re-execution and combine the progress made across all clients. Two clients are spawned with a different configuration compared to all other clients: The central synchronizing client does not receive a mutational stage, its only job is synchronization. The last client receives additional feedbacks with constant interestingness-values, which report data about the host system, such as available memory, to the monitor.

Communication between clients is done through Low Level Message Passing (LLMP), a shared memory-based message passing system provided by LibAFL. The absence of a requirement for kernel-based synchronization primitives such as locks allows FTZ to effectively scale across thousands of clients.

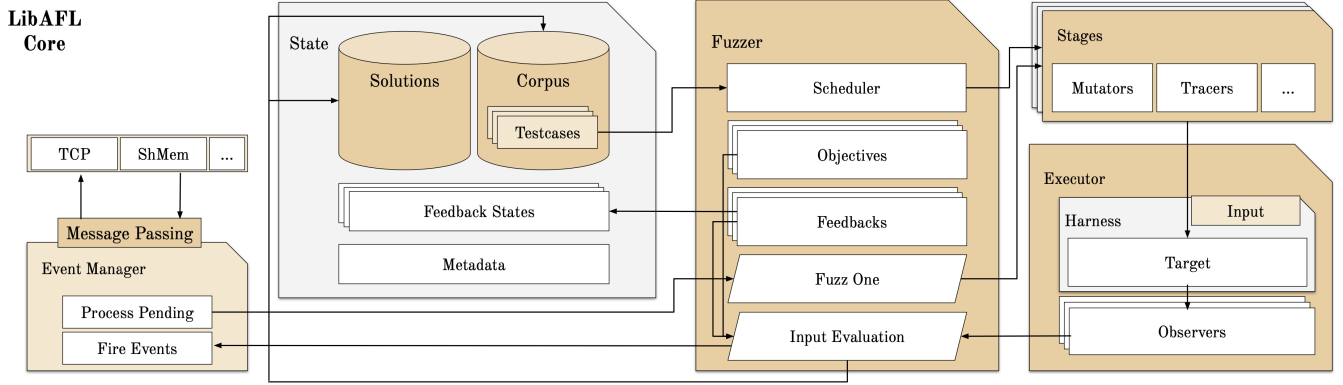


Figure 1: LibAFL’s Architecture [26]

Central monitoring is configurable in FTZ, but defaults to an `OnDiskJsonAggregateMonitor`, which will aggregate data across all clients and log it to a machine-readable file. Additionally, a graphical status-board, and a monitor relaying both a client’s logs and aggregated logs to the global logging system are provided. LibAFL further supports more complex logging to different data types or other systems such as a prometheus instance, all of which are easily integrated into FTZ.

4.6.2 Client Setup and Operation

Each client at the start of the fuzzing process initializes its own data structures. These include the following:

- A shared memory section to measure coverage in.
- A `ConstMapObserver` to handle the coverage, wrapped in a `HitcountsMapObserver` for binning postprocessing.
- A `TimeObserver` to measure execution time.
- A `PacketObserver` responsible for keeping track of transmitted packets, mapping states to a coverage-like map (refer to Section 4.5), and providing all required information for the current execution, such as a has of all packets for deduplication of inputs, the states and state-map for debugging purposes, and a base64-encoded packet capture (pcap) representation of the interaction, to allow graphical tools like Wireshark to be used in debugging.
- A `StdMapObserver` based on the map from the `PacketObserver`, to handle state coverage information.
- Combined feedback containing

- `MaxMapFeedbacks` for both code and state coverage information, the only feedbacks contributing values towards the interestingness of the current input.
- A `PacketMetadataFeedback` attaching the metadata provided by the `PacketObserver` to the testcase containing the input.
- A `TimeFeedback`, `InputLenFeedback`, and for the last client host system measuring feedbacks, attaching the execution time, input length, and other information to the metadata.

- Two corpi: a `InMemoryCorpus` for the working corpus of the fuzzer, and an `OnDiskCorpus` for all solutions found.
- A `StdState` containing a random number generator and the corpi.
- The appropriate mutators depending on the selected representation of the trace (see Section 4.4).
- `StdMOptMutator` is used as a mutator scheduler — it implements the algorithm first presented in MOpt [24].
- A `StdMutationalStage` wrapping the mutator scheduler and handling the main mutation workflow.
- A `StdWeightedScheduler` as an input selection scheduler with a power schedule, as known from AFL++ [10].
- A `ReplayingFuzzer` handling the main fuzzing loop — see below for more details.
- A custom `Executor` implementing all the necessary logic to interact with Zephyr — see below for more details.

After setting up all the required data structures, the corpus is filled based on a recorded trace (refer to Section 4.4.2). Because some of the trace subsets result in the same state coverage feedback, but they are still all useful to the fuzzer as starting points from mutations, they are force-generated and afterwards individually evaluated to enhance them with metadata.

Finally, the main fuzzing loop is started. Here, the fuzzer repeatedly calls the scheduler to select the next corpus entry to be mutated. Then, it calls the mutational stage to repeatedly select how many and which mutations to execute on a copy of the input and calls the evaluator in the fuzzer.

Here, the additional logic in **ReplayingFuzzer** compared to LibAFL’s built-in **StdFuzzer** comes into play. It sets up a map to store execution results in, and then repeatedly does the following:

1. First, the observers are reset.
2. Then, the input is passed to the executor to be run.
3. After that, postprocessing on observers is done.
4. The results from the observer(s), whose results are to be made more reliable, are hashed and combined with the exit status of the execution.
5. This combination is then used to index into the execution count map, where **ReplayingFuzzer** counts how often each result is measured.
6. Then, the measurements are evaluated as follows:
 - a. If a crash is observed, the fuzzer returns early from the loop to ensure all crashes are caught by the fuzzer.
 - b. If the results observed the most have been measured more than a configurable number more often than any other, and the latest execution results in the most common measurements, the execution results are assumed to be “correct” and returned.
 - c. If, after a configurable maximum number of executions, the fuzzer is still unable to get a decisive winner, the evaluation is short-circuited and the input is not added to either corpus.
7. Finally, the measured ratios are stored and reported to the monitor.

The executor receives the input, and starts its operation by marking the new run in the fuzzing client state and resetting the packet transmission buffers. Then, Zephyr is spawned in a subprocess with the

shared memory information for the coverage and network buffer as environment variables. FTZ then waits for Zephyr to startup, while logging packets emitted by it, and only responding to those that require a manual response (see Section 4.3).

After this interaction, the trace is converted to a list of raw byte vectors to be transmitted to Zephyr. One by one, the packets are sent to Zephyr and added to the **PacketObserver**. In between sending packets, FTZ waits for Zephyr to respond. Since there is currently no way to wait until Zephyr is done with processing an incoming packet, FTZ waits until a set time has expired since the last outgoing or incoming packet. During this phase, manual responses are emitted if appropriate. After the last packet was sent and no packet was received for the set timeout, the subprocess running Zephyr is shut down and checked for a crash to be reported.

There exists a balance between the inter-packet wait time and Zephyr’s `--rt-ratio` value (see Section 4.1) to maximize Zephyr’s consistency. If Zephyr is run too quickly, and the inter-packet wait time is set too long, the connection times out before the second packet is sent. In the opposite case, Zephyr may not be done processing a packet before the fuzzer attempts to send the next packet. Initial experiments showed the sweet spot to be at a `--rt-ratio` of 1 (thus running Zephyr according to the host’s real-time) and an inter-packet wait time of 100ms, interrupted 5 times to check for incoming packets.

4.6.3 Helper Functionality

FTZ contains additional logic helpful during development and triage of found issues. First, an implementation of the shared memory-based ethernet driver for the userland network client `smoltcp` allows manual interaction with Zephyr through shared memory. Additionally, a set of postprocessing scripts are available, which, among other things, extract pcap files from the corpus, and produce plots as shown in Section 5.

4.7 Contributions to LibAFL

During this project, I have contributed a range of improvements implemented for FTZ as generic version to LibAFL. These include:

- **MappingMutators** are essential for any project using compound input types — they allow mapping mutators targeting a certain type to those where the initial input type can be extracted from using custom logic. One such example

would be applying `havoc_mutations` to the payload field of the TCP packet.¹

- `CentralizedLauncherBuilder::overcommit` and `LauncherBuilder::overcommit` allows users to launch multiple fuzzing clients per CPU core. This is useful in specific projects like FTZ, where an individual client does not fully load a CPU core because of wait states necessary for e.g. synchronization.
- `int_mutators` include the applicable mutators from `havoc_mutations` targeting numeric types.
- `BoolMutators` flip boolean values.
- `ValueInput`, an improvement to how inputs encapsulating a simple data type are implemented.
- A set of macros for mapping and combining mutator lists and their types.
- Improved flexibility for certain schedulers to work on any observer.
- `OnDiskJsonAggregateMonitor` logs the data aggregated across all fuzzing clients at a certain interval to a file containing machine-readable data.
- Several general architectural and clean-code improvements.
- A generic adaptation of `ListInput`, including additional mutators and support for the existing `MultipartInput` — a simplified variant of `ListInput` with additional keys for each message.
- Several bugfixes related to `MultipartInput`.
- `StdFuzzer::with_bloom_input_filter`, an improvement to `StdFuzzer` which uses a probabilistic filter to reduce repeated execution of the same input²

5 Evaluation and Results

3.@Peter do I need explicit research questions here? Or is this clear by the headings and what I set up in the text (here and before)?

FTZ was evaluated along multiple axis, starting with experiments on the consistency of the target,

¹Currently, only non-crossover mutations are supported in FTZ, because of a limitation in LibAFL with using nested `MappingMutators`. This is required to map mutators from their raw target type (such as byte array or number) to the parsed input structure and then again to the composite type such as `ListInput`.

²Not currently used in FTZ.

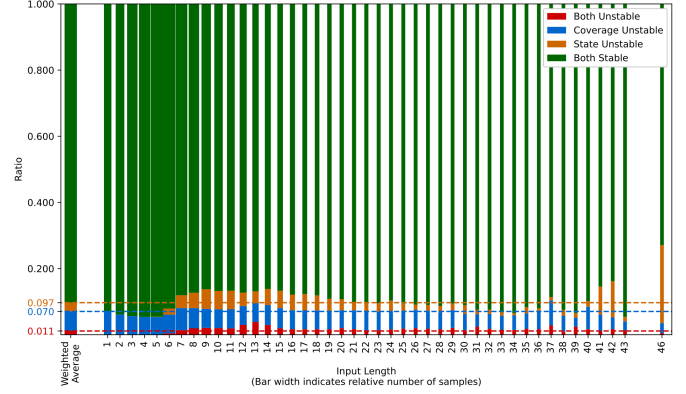


Figure 2: Average stability of both feedbacks across trace lengths

and then evaluating the effectiveness of the different improvements implemented in FTZ.

All experiments were performed on a 64-core AMD EPYC-Milan machine, using the configuration and parameters described in Section 4 unless indicated otherwise.

5.1 Consistency

To evaluate the consistency of the PUT when executed by the fuzzer, I changed FTZ to use `StdScheduler`, which selects inputs from the corpus at random, to generate a wider range of inputs. I further set up `ReplayingFuzzer` to evaluate input traces until the most common appears at least 100 times and a factor of 1.5 more often than any other input, up to 1500 executions per input.

When FTZ is setup to use both coverage and state-diff feedback, and requiring inputs to be consistent in both their coverage and state measurements, the results in Figure 2 are measured. The results for runs checking coverage and state-diff feedback exclusively can be found in Figures 3 and 4. All figures show the average stability measured across trace lengths. The evaluations were run across 64 cores, with 10 clients per core, for approximately 24 hours and 40 million target executions on individual feedbacks, and for 48 hours for the combined feedback.

4.Re-render plots at higher DPI, fix placement

To find the source of the different coverage maps measured across multiple executions of the same input, I added additional logging to `__sanitizer_cov_trace_pc_guard` (refer to Section 4.2), recording the guard index and the address the function returns to. The latter is used to map guard to source code location. At the same time, the differences between executions are mapped back to

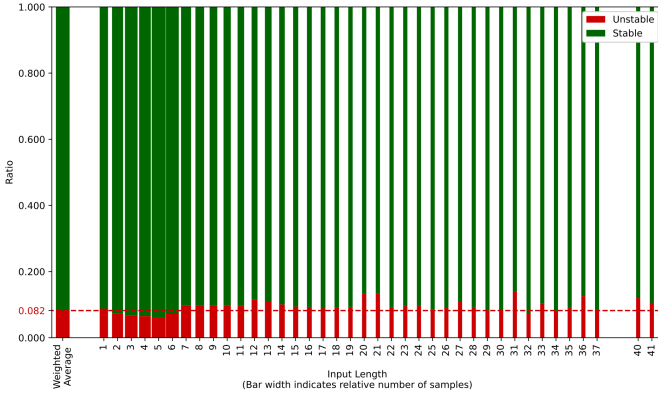


Figure 3: Average stability of coverage feedback across trace lengths

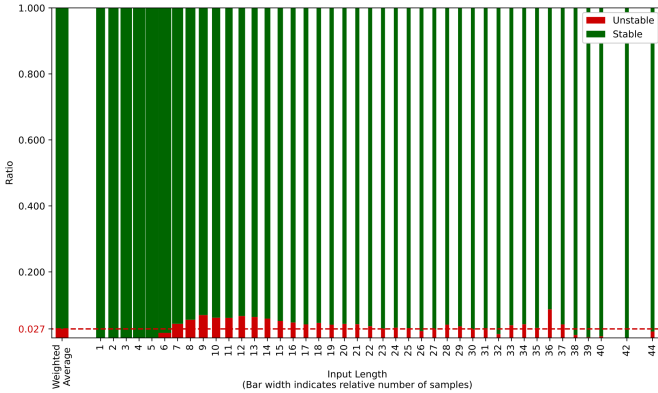


Figure 4: Average stability of state-diff feedback across trace lengths

guard index in the fuzzer and recorded. This information is then combined, and sorted by how often each guard appears. The most common functions appearing in this list are the following:

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`

Further notable entries include `net_ipv4_init`, `net_tcp_init`, and `net_init`. Across 137,571 executions of Zephyr, differences at 232,903 offsets in the coverage map were measured, the most common (`k_work_init_delayable`) appeared in 1745 executions, 73 of 386 entries found to not always be consistent appeared in fewer than 0.1% of all executions.

Discussion

Both coverage and state-diff results show inconsistencies when Zephyr is run by FTZ.

Distribution

Coverage As discussed in Section 4.2, for certain coverage entries, *how often* a certain basic block is executed is expected to be inconsistent because of inherent inconsistencies of the non-deterministic host scheduler. However, since FTZ only taints executed basic blocks, the differences measured are between a basic block being executed any number of times and the basic block not being executed at all. Functions such as `net_init` should be called on every launch, and if they are not executed, Zephyr may not be initialized correctly, thus invalidating any evaluation on it, indicating that the differences in coverage can not be ignored by FTZ. It is further notable that many of the functions in the list of inconsistently executed basic blocks appear to be related to system startup and initialization. Finally, coverage is measured with high consistency across trace length, which may suggest that the logic only executed sometimes is not related to packet handling.

While Section 5.2 explores how different configurations of Zephyr make both state and code coverage less stable at the host’s performance limit, I was unable to determine the fundamental source of these inconsistencies. Because of the high rate of inconsistency in the measurements of basic block coverage, I decided to not use it as feedback to the fuzzer

No.	Time	Protocol	Source	Destination	Length	Info
1	0.000000	ICMPv6	::	ff02::16	90	Multicast Listener Report Message v2
2	0.043495	ICMPv6	::	ff02::16	90	Multicast Listener Report Message v2
3	0.086996	ICMPv6	::	ff02::1:...	78	Neighbor Solicitation for fe80::5eff:fe00:5331
4	0.087045	ICMPv6	fe80::20...	ff02::16	110	Multicast Listener Report Message v2
5	0.130551	ICMPv6	::	ff02::2	62	Router Solicitation
6	0.130570	ICMPv6	fe80::20...	::	78	Router Advertisement from 00:00:5e:00:53:ff
7	0.174075	ICMPv6	::	ff02::16	90	Multicast Listener Report Message v2
8	0.217566	ICMPv6	::	ff02::1:...	78	Neighbor Solicitation for 2001:db8::1
9	0.217595	ICMPv6	fe80::20...	ff02::16	110	Multicast Listener Report Message v2
10	0.317841	TCP	192.0.2.2	192.0.2.1	74	41052 → 4242 [SYN] Seq=0 Win=64240 Len=0 MSS=1460 SACK_PERM TSval=3414956140 TSecr=0 WS=128
11	0.361360	ARP	02:00:5e...	Broadcast	42	Who has 192.0.2.2? Tell 192.0.2.1
12	0.361365	ARP	ICANNIAN...	02:00:5e...	42	192.0.2.2 is at 02:00:5e:00:53:31
13	0.404856	TCP	192.0.2.1	192.0.2.2	58	4242 → 41052 [SYN, ACK] Seq=0 Ack=1 Win=1536 Len=0 MSS=1460
14	0.505074	TCP	192.0.2.2	192.0.2.1	54	41052 → 4242 [ACK] Seq=1 Ack=1 Win=64240 Len=0
15	0.605329	TCP	192.0.2.2	192.0.2.1	61	41052 → 4242 [PSH, ACK] Seq=1 Ack=1 Win=64240 Len=7
16	0.648829	TCP	192.0.2.1	192.0.2.2	54	4242 → 41052 [ACK] Seq=1 Ack=8 Win=1529 Len=0
17	0.692331	TCP	192.0.2.1	192.0.2.2	61	4242 → 41052 [PSH, ACK] Seq=1 Ack=8 Win=1536 Len=7
18	0.792593	TCP	192.0.2.2	192.0.2.1	54	24483 → 63262 [FIN, SYN, ACK, AE] Seq=0 Ack=1 Win=64236 Len=0
19	0.836089	TCP	192.0.2.1	192.0.2.2	54	63262 → 24483 [RST] Seq=1 Win=0 Len=0
20	0.938582	TCP	192.0.2.2	192.0.2.1	74	41054 → 4242 [SYN, ACK] Seq=0 Ack=1 Win=64240 Len=0 MSS=1460 SACK_PERM TSval=3414956140 TSecr=0 WS=128
21	0.982101	TCP	192.0.2.1	192.0.2.2	61	[TCP Retransmission] 4242 → 41052 [PSH, ACK] Seq=1 Ack=8 Win=1536 Len=7
22	1.025987	TCP	192.0.2.1	192.0.2.2	54	4242 → 41054 [RST] Seq=1 Win=0 Len=0
23	1.102896	ICMPv6	fe80::5e...	ff02::2	70	Router Solicitation from 02:00:5e:00:53:31
24	1.102917	ICMPv6	fe80::20...	fe80::5e...	78	Router Advertisement from 00:00:5e:00:53:ff
25	1.146419	ICMPv6	fe80::5e...	ff02::1:...	86	Neighbor Solicitation for fe80::200:5eff:fe00:53ff from 02:00:5e:00:53:31
26	1.146448	ICMPv6	fe80::20...	ff02::16	110	Multicast Listener Report Message v2
27	1.189975	ICMPv6	fe80::5e...	ff02::1:...	86	Neighbor Solicitation for fe80::200:5eff:fe00:53ff from 02:00:5e:00:53:31
28	1.190002	ICMPv6	fe80::20...	ff02::16	110	Multicast Listener Report Message v2
29	1.290222	TCP	192.0.2.2	192.0.2.1	54	41052 → 4242 [ACK] Seq=1 Ack=1 Win=64240 Len=0
30	1.333727	TCP	192.0.2.1	192.0.2.2	54	4242 → 41052 [ACK] Seq=1 Ack=8 Win=1536 Len=0
31	1.410656	TCP	192.0.2.1	192.0.2.2	61	[TCP Retransmission] 4242 → 41052 [PSH, ACK] Seq=1 Ack=8 Win=1536 Len=7
No.	Time	Protocol	Source	Destination	Length	Info
1	0.000000	ICMPv6	::	ff02::16	90	Multicast Listener Report Message v2
2	0.043494	ICMPv6	::	ff02::16	90	Multicast Listener Report Message v2
3	0.086996	ICMPv6	::	ff02::1:...	78	Neighbor Solicitation for fe80::5eff:fe00:5331
4	0.087067	ICMPv6	fe80::20...	ff02::16	110	Multicast Listener Report Message v2
5	0.130567	ICMPv6	::	ff02::2	62	Router Solicitation
6	0.130588	ICMPv6	fe80::20...	::	78	Router Advertisement from 00:00:5e:00:53:ff
7	0.174104	ICMPv6	::	ff02::16	90	Multicast Listener Report Message v2
8	0.218412	ICMPv6	::	ff02::1:...	78	Neighbor Solicitation for 2001:db8::1
9	0.218440	ICMPv6	fe80::20...	ff02::16	110	Multicast Listener Report Message v2
10	0.318665	TCP	192.0.2.2	192.0.2.1	74	41052 → 4242 [SYN] Seq=0 Win=64240 Len=0 MSS=1460 SACK_PERM TSval=3414956140 TSecr=0 WS=128
11	0.362177	ARP	02:00:5e...	Broadcast	42	Who has 192.0.2.2? Tell 192.0.2.1
12	0.362182	ARP	ICANNIAN...	02:00:5e...	42	192.0.2.2 is at 02:00:5e:00:53:31
13	0.405706	TCP	192.0.2.1	192.0.2.2	58	4242 → 41052 [SYN, ACK] Seq=0 Ack=1 Win=1536 Len=0 MSS=1460
14	0.505963	TCP	192.0.2.2	192.0.2.1	54	41052 → 4242 [ACK] Seq=1 Ack=1 Win=64240 Len=0
15	0.606165	TCP	192.0.2.2	192.0.2.1	61	41052 → 4242 [PSH, ACK] Seq=1 Ack=1 Win=64240 Len=7
16	0.649661	TCP	192.0.2.1	192.0.2.2	54	4242 → 41052 [ACK] Seq=1 Ack=8 Win=1529 Len=0
17	0.693155	TCP	192.0.2.1	192.0.2.2	61	4242 → 41052 [PSH, ACK] Seq=1 Ack=8 Win=1536 Len=7
18	0.793417	TCP	192.0.2.2	192.0.2.1	54	24483 → 63262 [FIN, SYN, ACK, AE] Seq=0 Ack=1 Win=64236 Len=0
19	0.836926	TCP	192.0.2.1	192.0.2.2	54	63262 → 24483 [RST] Seq=1 Win=0 Len=0
20	0.937257	TCP	192.0.2.2	192.0.2.1	74	41054 → 4242 [SYN, ACK] Seq=0 Ack=1 Win=64240 Len=0 MSS=1460 SACK_PERM TSval=3414956140 TSecr=0 WS=128
21	0.980767	TCP	192.0.2.1	192.0.2.2	61	[TCP Retransmission] 4242 → 41052 [PSH, ACK] Seq=1 Ack=8 Win=1536 Len=7
22	1.024283	TCP	192.0.2.1	192.0.2.2	54	4242 → 41054 [RST] Seq=1 Win=0 Len=0
23	1.124470	TCP	192.0.2.2	192.0.2.1	54	41052 → 4242 [ACK] Seq=1 Ack=1 Win=64240 Len=0
24	1.134549	ICMPv6	fe80::5e...	ff02::2	70	Router Solicitation from 02:00:5e:00:53:31
25	1.134568	ICMPv6	fe80::20...	fe80::5e...	78	Router Advertisement from 00:00:5e:00:53:ff
26	1.178064	ICMPv6	fe80::5e...	ff02::1:...	86	Neighbor Solicitation for fe80::200:5eff:fe00:53ff from 02:00:5e:00:53:31
27	1.178094	ICMPv6	fe80::20...	ff02::16	110	Multicast Listener Report Message v2
28	1.221590	ICMPv6	fe80::5e...	ff02::1:...	86	Neighbor Solicitation for fe80::200:5eff:fe00:53ff from 02:00:5e:00:53:31
29	1.221619	ICMPv6	fe80::20...	ff02::16	110	Multicast Listener Report Message v2
No.	Time	Protocol	Source	Destination	Length	Info
1	0.000000	ICMPv6	::	ff02::16	90	Multicast Listener Report Message v2
2	0.043496	ICMPv6	::	ff02::16	90	Multicast Listener Report Message v2
3	0.086990	ICMPv6	::	ff02::1:...	78	Neighbor Solicitation for fe80::5eff:fe00:5331
4	0.087038	ICMPv6	fe80::20...	ff02::16	110	Multicast Listener Report Message v2
5	0.130527	ICMPv6	::	ff02::2	62	Router Solicitation
6	0.130539	ICMPv6	fe80::20...	::	78	Router Advertisement from 00:00:5e:00:53:ff
7	0.174036	ICMPv6	::	ff02::16	90	Multicast Listener Report Message v2
8	0.217504	ICMPv6	::	ff02::1:...	78	Neighbor Solicitation for 2001:db8::1
9	0.217527	ICMPv6	fe80::20...	ff02::16	110	Multicast Listener Report Message v2
10	0.317780	TCP	192.0.2.2	192.0.2.1	74	41052 → 4242 [SYN] Seq=0 Win=64240 Len=0 MSS=1460 SACK_PERM TSval=3414956140 TSecr=0 WS=128
11	0.361269	ARP	02:00:5e...	Broadcast	42	Who has 192.0.2.2? Tell 192.0.2.1
12	0.361272	ARP	ICANNIAN...	02:00:5e...	42	192.0.2.2 is at 02:00:5e:00:53:31
13	0.406530	TCP	192.0.2.1	192.0.2.2	58	4242 → 41052 [SYN, ACK] Seq=0 Ack=1 Win=1536 Len=0 MSS=1460
14	0.506769	TCP	192.0.2.2	192.0.2.1	54	41052 → 4242 [ACK] Seq=1 Ack=1 Win=64240 Len=0
15	0.609098	TCP	192.0.2.2	192.0.2.1	61	41052 → 4242 [PSH, ACK] Seq=1 Ack=1 Win=64240 Len=7
16	0.652594	TCP	192.0.2.1	192.0.2.2	54	4242 → 41052 [ACK] Seq=1 Ack=8 Win=1529 Len=0
17	0.696031	TCP	192.0.2.1	192.0.2.2	61	4242 → 41052 [PSH, ACK] Seq=1 Ack=8 Win=1536 Len=7
18	0.796311	TCP	192.0.2.2	192.0.2.1	54	24483 → 63262 [FIN, SYN, ACK, AE] Seq=0 Ack=1 Win=64236 Len=0
19	0.839879	TCP	192.0.2.1	192.0.2.2	54	63262 → 24483 [RST] Seq=1 Win=0 Len=0
20	0.940128	TCP	192.0.2.2	192.0.2.1	74	41054 → 4242 [SYN, ACK] Seq=0 Ack=1 Win=64240 Len=0 MSS=1460 SACK_PERM TSval=3414956140 TSecr=0 WS=128
21	0.983637	TCP	192.0.2.1	192.0.2.2	54	4242 → 41054 [RST] Seq=1 Win=0 Len=0
22	1.027171	TCP	192.0.2.1	192.0.2.2	61	[TCP Retransmission] 4242 → 41052 [PSH, ACK] Seq=1 Ack=8 Win=1536 Len=7
23	1.105341	ICMPv6	fe80::5e...	ff02::2	70	Router Solicitation from 02:00:5e:00:53:31
24	1.105361	ICMPv6	fe80::20...	fe80::5e...	78	Router Advertisement from 00:00:5e:00:53:ff
25	1.148859	ICMPv6	fe80::5e...	ff02::1:...	86	Neighbor Solicitation for fe80::200:5eff:fe00:53ff from 02:00:5e:00:53:31
26	1.148887	ICMPv6	fe80::20...	ff02::16	110	Multicast Listener Report Message v2
27	1.192476	ICMPv6	fe80::5e...	ff02::1:...	86	Neighbor Solicitation for fe80::200:5eff:fe00:53ff from 02:00:5e:00:53:31
28	1.192508	ICMPv6	fe80::20...	ff02::16	110	Multicast Listener Report Message v2
29	1.292761	TCP	192.0.2.2	192.0.2.1	54	41052 → 4242 [ACK] Seq=1 Ack=1 Win=64240 Len=0
30	1.336266	TCP	192.0.2.1	192.0.2.2	54	4242 → 41052 [ACK] Seq=1 Ack=8 Win=1536 Len=0

Figure 5: Packets exchanged for the same input in 10 executions, recorded 4, 4, and 2 times respectively

in FTZ. However, the values can still be used as a heuristic to measure the fuzzer’s ability to test all system parts recorded at any part in any execution. Since `MaxMapFeedback` records map entries present in *any* map passed to it, even if a certain function is not called in one execution because something went wrong, e.g. during Zephyr’s initialization logic, the same function is likely to be triggered in one of the other executions.

State-Diff The differences as measured by the state-diff observer indicates a difference in packets received by the fuzzer. This could be confirmed by manual inspection of the different interactions between the fuzzer and Zephyr from the same input. As described in Sections 4.6.2 and 4.6.3, FTZ provides functionality to extract these into `pcap` files. Figure 5 shows screenshots of three different exchanges recorded for 10 executions with the same input.

Like in the example, retransmitted packets and those resetting the connection appear frequently. However, I was unable to find a reason for the inconsistencies or a definite pattern between them.

Unlike with basic block coverage, state-diff coverage seems to be trace-length dependent: Traces with length ≤ 5 are almost always consistent with respect to the packets exchanged between fuzzer and Zephyr. However, the ratio does not continue rising with increased trace length after that, as would be expected if the error rate is independent of state and packet. This suggests that there remains an unknown factor influencing reliability of Zephyr’s responses. The fact that short traces are executed comparatively consistently may be caused by either a filling buffer in Zephyr or an underlying problem requiring Zephyr to be in a state only reachable with a certain number of packets.

Distribution The consistencies of both feedbacks show a further notable statistic: There seems to be a set of inputs triggering inconsistent behavior more likely than others. Figure 6 shows the distribution of ratios between the incorrect and correct measurements across trace lengths. For an input that provoked three different observer values appearing 2, 10, and 100 times, this ratio would therefore be 0.12. There appear two sections along the y-axis with higher densities, at approximately 0.1 and 0.75 respectively, with fewer inputs resulting in consistencies at around 0.4. The same effect does not appear when coverage feedback is used (see Figure 8), and significantly less pronounced when using both feedbacks (see Figure 7). The latter can be explained by the fact that coverage is less consistent than state-diff, overpowering its effects.

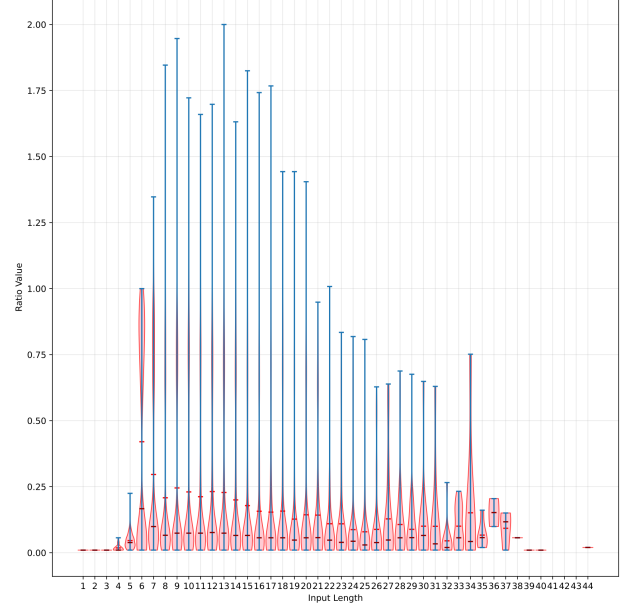


Figure 6: Ratio between incorrect and correct observer measurements across trace lengths when using state-diff feedback (violin width indicates density)

I was unable to create sufficient proof of this conjecture during this thesis, nor find a correlation between the actual traces that would explain this behavior.

5.2 Throughput and Overcommit

When spawning a single fuzzing client per core, as is usual in fuzzing, the CPU time load averages approximately 0.8% in user space and 1.9 in system space. Increasing the `overcommit` value and thus the number of clients per core increases instability rates for both observers, as seen in Figure 9. However, it simultaneously increases the overall execution speed of the fuzzer up to a certain point, as seen in Figure 10. The CPU loads for `overcommit` values of 10, 20, and 50 are 3.9%/10.1%, 8.7%/23.1%, and 8.3%/89.9% respectively.

Discussion

As described in Section 4.6.2, executing a single input on Zephyr leads to a dominating number wait states in both Zephyr and the fuzzer needed for synchronization. Even when increasing the number of clients per core to a level where the CPU is far from being fully loaded increases the inconsistency rate, suggesting the limitation of FTZ is in scheduling the number of processes requiring precise timing for their execution consistency. When fully loading the CPU, the execution speed collapses by approximately a factor

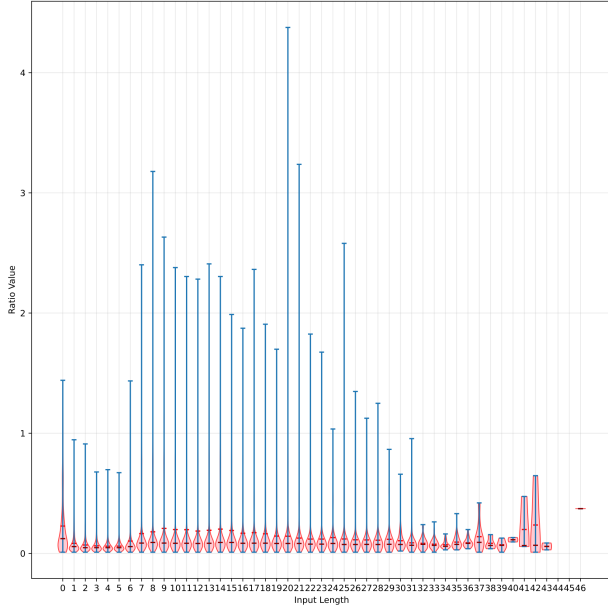


Figure 7: Ratio between incorrect and correct observer measurements across trace lengths when using both feedbacks (violin width indicates density)

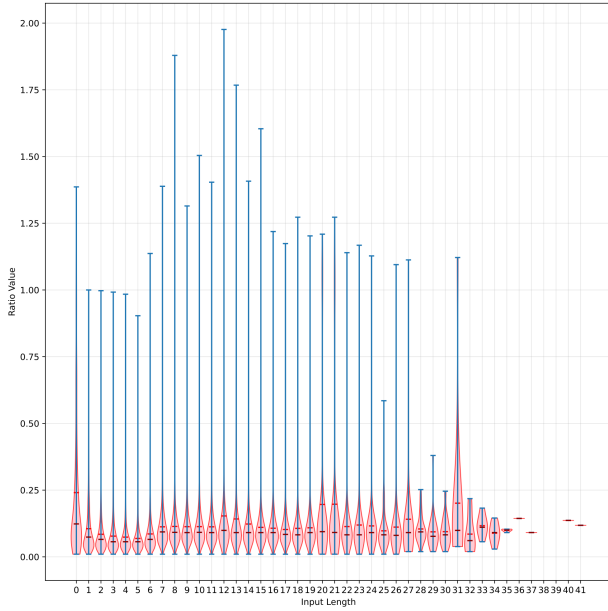


Figure 8: Ratio between incorrect and correct observer measurements across trace lengths when using coverage feedback (violin width indicates density)

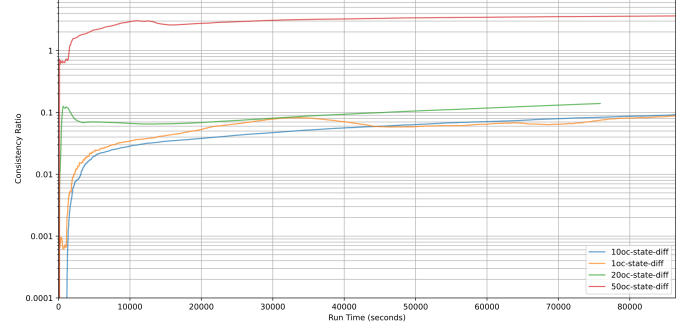


Figure 9: Consistencies across different overcommit values

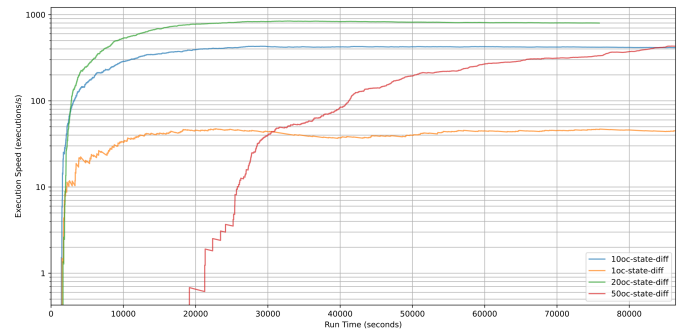


Figure 10: Execution speed across different overcommit values

10 compared to linear scaling, suggesting a bottleneck besides CPU load.

To mitigate increased inconsistency rates, **ReplayingFuzzer** has to be configured to re-execute each input more often, slowing throughput of new inputs down, thus negating some (or even all) of the gained speed. Since the error rates remain approximately consistent for **overcommit** values of up to 10, the remaining evaluations were done with FTZ configured to run 10 clients per core.

5.3 State Feedback vs. State-Diff Feedback

Figure 11 shows the coverage achieved by the different configurations of FTZ. Note that FTZ is configured to measure coverage across all parts of Zephyr, and is therefore unlikely to achieve code coverage of 100%, as many parts of the logic are not currently examined by FTZ. The most stark difference is between the configurations that rely on direct state feedback and those using state-diff feedback.

Figure 12 shows that FTZ exhausts all achievable states within the first hours, including propagation to the found inputs to all 640 clients, and is unable to find any further improvements after that. Note that FTZ is very unlikely to achieve a state coverage of 100%, as Zephyr is not built to emit every combination of flags in the TCP header. Figure 13 further corroborates this by showing that no inputs are added to the corpus after that.

Discussion

The number of states that can be emitted by Zephyr seems too small to make direct state feedback an effective feedback mechanism for FTZ. It may however still improve a fuzzer if it is combined with another form of feedback, like code coverage. This was however not further evaluated due to the unreliability of coverage measurements in FTZ (see Section 5.1).

5.4 Mutation Target Selection

Section 4.4.1 introduced how FTZ can be configured to mutate either a random message in a trace or always focus on the last message. Figure 11 shows a small difference between the two options, for both byte array and parsed message representation. While the difference is larger in the early stages of the fuzzing campaign, selecting the last message as a mutation target is shown to be more effective even after 24 hours.

Figure 14 further demonstrates that the strategy always mutating the last message is also more effective

and efficient at covering all possible state-diff map entries.

Discussion

When randomly selecting a message to mutate, FTZ with a certain probability selects the last message, which may explain why after a while, it catches up to the alternative strategy of always mutating the last message. This further suggests that the assumption described in Section 4.4.1 holds, and mutating early messages in long traces often renders the remainder of the trace useless, as the interdependencies between states and messages is broken.

5.5 Input Modelling and Mutation

Figures 11 and 14 show that modelling messages as a parsed data structure is more effective and efficient at maximizing code coverage and state-diff coverage.

Discussion

When modelling messages as a parsed structure, FTZ is severely limited in the possible input space it can explore. It can only output fixed layer 2 and 3 headers (except for their fields that depend on the packet contents), and even the TCP header always has a correct length field and checksum. However, these experiments show that this actually helps FTZ to test more parts of Zephyr.

Byte array modelling of inputs and random mutation in theory is more powerful — it can generate inputs that invalidate only one of the fixed values listed above — it is very unlikely to randomly generate the correct values for all others. This further means that Zephyr will reject most packets generated by such mutation in its first parsing layer, while deeper logic is never reached. The additional logic reached by FTZ in this configuration is exclusively due to the appending mutators, one of which will generate random valid TCP packets.**5.proof**

6 Conclusion

6.1 Limitations and Future Work

While this thesis presents a functional proof-of-concept fuzzer in FTZ, as discussed in Section 5, there remain a set of improvements to implement and questions it was unable to answer. First, sleep-interrupted busy waiting in both the fuzzer and Zephyr could be replaced by a form of kernel-supplied synchronization technique such as semaphores. There further is a list of efficiency improvements, such as incremental

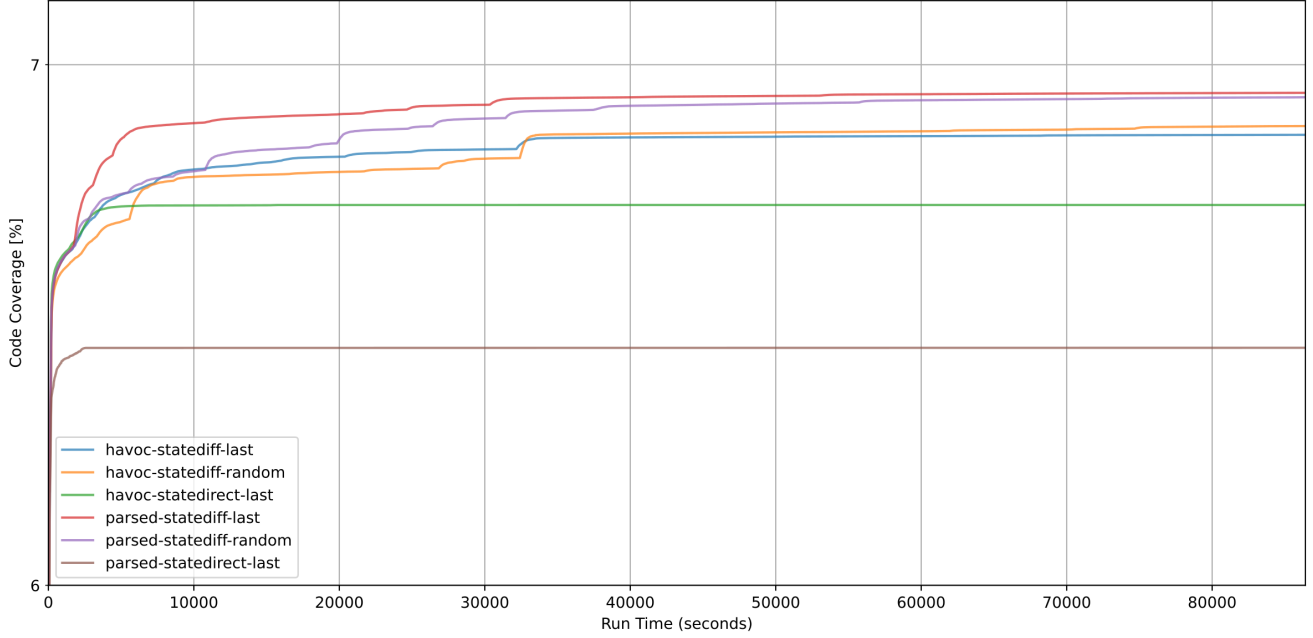


Figure 11: Code coverage across different configurations

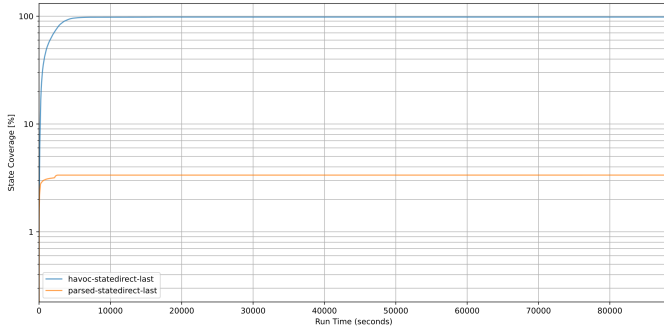


Figure 12: States in replies recorded by FTZ when configured using direct state feedback

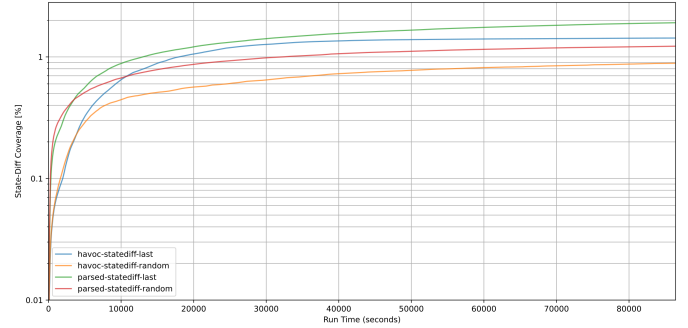


Figure 14: State-diff feedback covered by different configurations of FTZ

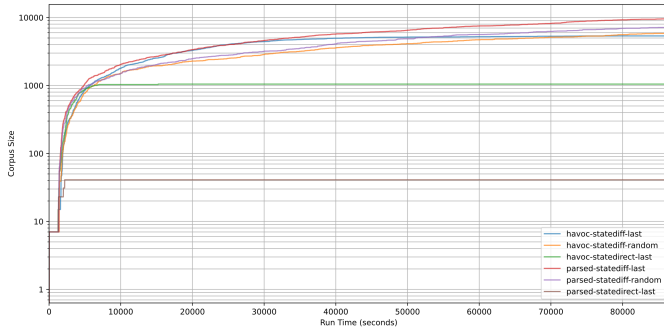


Figure 13: Number of corpus entries across different configurations

packet parsing, that were not completed because FTZ is not primarily constrained by CPU load but instead consistency.

First, prior work has shown that the seeds used in a fuzzer have a significant impact on the fuzzer's performance [58]. FTZ currently relies on subsets of a single recorded interaction, which could be extended with other traces, specifically those exercising different paths through the state machine, such as cancelled or otherwise incomplete interactions may prove beneficial for FTZ's performance.

Additional seeding could further improve the range of packets supported by the fuzzer: Support for TCP over IPv6 would require only little additional engineering in combination with additional seeds. Sim-

ilarly, options in the different protocol headers (see Section 2.2.2) are currently only partially fuzzed when using parsed input structures, which could be improved by additional seeds in addition to a list of additional mutators.

TCP-Fuzz [39] correctly identified that TCP/IP stacks have an input space larger than that of the packets they process in their configuration and invocation through system calls (see Section 3.3). These are currently not mutated in FTZ but instead fixed to the configuration of the `sockets/echo` sample (see Section 4).

FTZ further could be used as a basis to fuzz other protocols at different networking layers, such as application layer protocol implementations of an FTP or SMTP server or additional transport layer protocols like QUIC. This may further allow comparison between FTZ and previous work on these protocols (refer to Section 3.2).

However, the same challenges as outlined in Section 3.2.3 remain. Comparing FTZ to other approaches would either require reengineering other fuzzer’s target interaction to be compatible with Zephyr, or extracting the improvements made by FTZ and build a fuzzer around them targeting other code. Improvements made to LibAFL would make protocol fuzzing in general easier, but it still requires setting up the appropriate parsed data structured and mutators. However, this work could further confirm the results described in Section 5 independent of Zephyr or TCP/IP.

Alternatively, FTZ could be evaluated on other implementations of TCP/IP stacks, such as userland implementations (Section 4.6.3 discusses how one such implementation is already partially integrated into FTZ), or the network stacks of other OSs. The main challenge in this is the adaptation of the target similar to what is described in Section 4, such as sanitizer and code coverage instrumentation and drivers for the shared memory-based pseudo-networking or an alternate way of exchanging packets. Access to alternate implementations would also allow FTZ to implement differential fuzzing, testing the behavior of the different targets against each other to find logic errors that do not corrupt the memory and thus cannot currently be found by FTZ.

Finally, one could investigate how state information could be used besides feedback. Section 3.2.2 discusses advancements other projects have shown by using state information in other parts of the fuzzer, such as the scheduler.

6.2 Contributions and Summary

This thesis presents FTZ, a proof-of-concept fuzzer targeting the TCP/IP stack of Zephyr. To achieve this, it introduces a custom ethernet driver based on shared memory to reduce host kernel dependencies. `native_sim`, the environment simulation wrapper, is used to run Zephyr without the need for a dynamic emulation layer. It is built on and extends the fuzzing framework LibAFL.

In addition to initial investigation into the reasons for Zephyr’s at times unpredictable behavior, I evaluated the differences in performance of mutations on serialized and parsed packet representations, two strategies to select which message in a trace to mutate, and two heuristics to estimate the TCP state of a connection based on returned packets.

The experiments show that even limited structure-aware mutation is more efficient at covering both code coverage and the state space compared to naïve random mutation. In addition to appending new packets, mutating the last message of a trace is more efficient than selecting a random message to mutate. Finally, I present that maximizing simple state feedback as calculated by the heuristic quickly saturates the possible state space after which FTZ no longer makes any progress. Conversely, maximizing coverage across state transitions proves to be more effective.

In the interest of open science, the source code and all artifacts produced during this project are publicly available and released under an open-source license. During development, thousands of lines of code have been introduced to multiple upstream projects. All artifacts produced for this project are available at

github.com/riesentoaster/fuzzing-zephyr-network-stack. **6.change url**

Bibliography

- [1] “About the zephyr project.” (n.d.), [Online]. Available: <https://www.zephyrproject.org/learn-about/> (visited on Jan. 30, 2025).
- [2] “Real-time operating system.” (n.d.), [Online]. Available: https://en.wikipedia.org/wiki/Real-time_operating_system (visited on Jan. 30, 2025).
- [3] “Products running zephyr.” (n.d.), [Online]. Available: <https://www.zephyrproject.org/products-running-zephyr/> (visited on Jan. 30, 2025).
- [4] S. Mallisery and Y.-S. Wu, “Demystify the fuzzing methods: A comprehensive survey,” *ACM Comput. Surv.*, vol. 56, no. 3, Oct. 2023, ISSN: 0360-0300. DOI: 10.1145/3623375. [Online]. Available: <https://doi.org/10.1145/3623375>.
- [5] P. Godefroid, M. Y. Levin, and D. Molnar, “Automated whitebox fuzz testing,” Nov. 2008. [Online]. Available: <https://www.microsoft.com/en-us/research/publication/automated-whitebox-fuzz-testing/>.
- [6] R. McNally, K. K.-H. Yiu, D. A. Grove, and D. Gerhardy, “Fuzzing: The state of the art,” *DSTO Defence Science and Technology Organisation*, Feb. 2012.
- [7] J. Methman. “Clusterfuzzlite: Continuous fuzzing for all.” (Nov. 2021), [Online]. Available: <https://security.googleblog.com/2021/11/clusterfuzzlite-continuous-fuzzing-for.html> (visited on Feb. 5, 2025).
- [8] B. P. Miller, L. Fredriksen, and B. So, “An Empirical Study of the Reliability of UNIX Utilities,” *Commun. ACM*, vol. 33, no. 12, pp. 32–44, Dec. 1990, ISSN: 0001-0782. DOI: 10.1145/96267.96279. [Online]. Available: <https://doi.org/10.1145/96267.96279>.
- [9] “Google scholar — fuzz testing.” (2025), [Online]. Available: <https://scholar.google.com/scholar?q=fuzz+testing> (visited on Jan. 30, 2025).
- [10] A. Fioraldi, D. Maier, H. Eißfeldt, and M. Heuse, “AFL++ : Combining incremental steps of fuzzing research,” in *14th USENIX Workshop on Offensive Technologies (WOOT 20)*, USENIX Association, Aug. 2020. [Online]. Available: <https://www.usenix.org/conference/woot20/presentation/fioraldi>.
- [11] “Syzkaller - kernel fuzzer.” (n.d.), [Online]. Available: <https://github.com/google/syzkaller> (visited on Feb. 5, 2025).
- [12] “Libfuzzer — a library for coverage-guided fuzz testing.” (n.d.), [Online]. Available: <https://lvm.org/docs/LibFuzzer.html> (visited on Feb. 5, 2025).
- [13] “Honggfuzz.” (n.d.), [Online]. Available: <https://honggfuzz.dev> (visited on Feb. 5, 2025).
- [14] “Oss-fuzz.” (n.d.), [Online]. Available: <https://github.io/oss-fuzz/> (visited on Feb. 5, 2025).
- [15] A. Zeller, R. Gopinath, M. Böhme, G. Fraser, and C. Holler, *The Fuzzing Book*. CISA Helmholtz Center for Information Security, 2024, Retrieved 2024-07-01 16:50:18+02:00. [Online]. Available: <https://www.fuzzingbook.org/>.
- [16] P. Cai, “Kernel- vs. user-level networking: A ballad of interrupts and how to mitigate them,” M.S. thesis, University of Waterloo, 2023.
- [17] H. Liang, X. Pei, X. Jia, W. Shen, and J. Zhang, “Fuzzing: State of the art,” *IEEE Transactions on Reliability*, vol. 67, no. 3, pp. 1199–1218, 2018. DOI: 10.1109/TR.2018.2834476.
- [18] H. Peng, Y. Shoshitaishvili, and M. Payer, “T-fuzz: Fuzzing by program transformation,” in *2018 IEEE Symposium on Security and Privacy (SP)*, 2018, pp. 697–710. DOI: 10.1109/SP.2018.00056.
- [19] C. Aschermann, S. Schumilo, T. Blazytko, R. Gawlik, and T. Holz, “Redqueen: Fuzzing with input-to-state correspondence,” in *Proceedings of the 2016 Network and Distributed System Security Symposium (NDSS)*, vol. 19, 2019, pp. 1–15.
- [20] C. Daniele, S. B. Andarzian, and E. Poll, “Fuzzers for stateful systems: Survey and research directions,” *ACM Comput. Surv.*, vol. 56, no. 9, Apr. 2024, ISSN: 0360-0300. DOI: 10.1145/3648468. [Online]. Available: <https://doi.org/10.1145/3648468>.
- [21] M. Boehme, C. Cadar, and A. ROYCHOUDHURY, “Fuzzing: Challenges and reflections,” *IEEE Software*, vol. 38, no. 3, pp. 79–86, 2021. DOI: 10.1109/MS.2020.3016773.
- [22] J. Ba, M. Böhme, Z. Mirzamomen, and A. Roychoudhury, “Stateful greybox fuzzing,” in *31st USENIX Security Symposium (USENIX Security 22)*, Boston, MA: USENIX Association, Aug. 2022, pp. 3255–3272, ISBN: 978-1-939133-31-1. [Online]. Available: <https://www.usenix.org/conference/usenixsecurity22/presentation/ba>.
- [23] B. Zhao, Z. Li, S. Qin, *et al.*, “StateFuzz: System Call-Based State-Aware linux driver fuzzing,” in *31st USENIX Security Symposium (USENIX Security 22)*, Boston, MA: USENIX Association, Aug. 2022, pp. 3273–3289, ISBN: 978-1-939133-31-1. [Online]. Available: <https://www.usenix.org/conference/usenixsecurity22/presentation/zhao-bodong>.
- [24] C. Lyu, S. Ji, C. Zhang, *et al.*, “MOPT: Optimized mutation scheduling for fuzzers,” in *28th USENIX Security Symposium (USENIX Security 19)*, Santa Clara, CA: USENIX Association, Aug. 2019, pp. 1949–1966, ISBN: 978-1-939133-06-9. [Online]. Available: <https://www.usenix.org/conference/usenixsecurity19/presentation/lyu>.
- [25] “American fuzzy lop — whitepaper.” (n.d.), [Online]. Available: https://lcamtuf.coredump.cx/afl/technical_details.txt (visited on Feb. 5, 2025).
- [26] A. Fioraldi, D. Maier, D. Zhang, and D. Balzarotti, “LibAFL: A Framework to Build Modular and Reusable Fuzzers,” in *Proceedings of the 29th ACM conference on Computer and communications security (CCS)*, ser. CCS ’22, Los Angeles, U.S.A.: ACM, Nov. 2022.
- [27] “Zephyr documentation — fuzzing.” (n.d.), [Online]. Available: <https://docs.zephyrproject.org/latest/samples/subsys/debug/fuzz/README.html> (visited on Feb. 6, 2025).
- [28] “Zephyr sample project — fuzz.” (n.d.), [Online]. Available: <https://github.com/zephyrproject-rtos/zephyr/tree/main/samples/subsys/debug/fuzz> (visited on Feb. 6, 2025).
- [29] “Fuzzbuzz — zephyr’s fuzzing example.” (n.d.), [Online]. Available: <https://github.com/fuzzbuzz/fuzz-zephyr> (visited on Feb. 6, 2025).
- [30] “Fuzzing zephyr with afl and renode.” (Oct. 2023), [Online]. Available: <https://www.zephyrproject.org/fuzzing-zephyr-with-afl-and-renode/> (visited on Feb. 6, 2025).

- [31] D. K. Oka and T. Makila, "A practical guide to fuzz testing embedded software in a ci pipeline," *FISITA World Congress 2021 - Technical Programme*, 2021.
- [32] X. Zhang, C. Zhang, X. Li, et al., "A survey of protocol fuzzing," *ACM Comput. Surv.*, vol. 57, no. 2, Oct. 2024, issn: 0360-0300. DOI: 10.1145/3696788. [Online]. Available: <https://doi.org/10.1145/3696788>.
- [33] X. Wei, Z. Yan, and X. Liang, "A survey on fuzz testing technologies for industrial control protocols," *Journal of Network and Computer Applications*, vol. 232, p. 104020, 2024, issn: 1084-8045. DOI: <https://doi.org/10.1016/j.jnca.2024.104020>. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S1084804524001978>.
- [34] R. Natella and V.-T. Pham, "ProFuzzBench: A benchmark for stateful protocol fuzzing," in *Proceedings of the 30th ACM SIGSOFT International Symposium on Software Testing and Analysis*, ser. ISSTA 2021, Virtual, Denmark: Association for Computing Machinery, 2021, pp. 662–665, isbn: 9781450384599. DOI: 10.1145/3460319.3469077. [Online]. Available: <https://doi.org/10.1145/3460319.3469077>.
- [35] R. Natella, "Stateaff: Greybox fuzzing for stateful network servers," *Empirical Software Engineering*, vol. 27, no. 7, p. 191, Oct. 2022, issn: 1573-7616. DOI: 10.1007/s10664-022-10233-3. [Online]. Available: <https://doi.org/10.1007/s10664-022-10233-3>.
- [36] R. Helmke, E. Winter, and M. Rademacher, "EpF: An evolutionary, protocol-aware, and coverage-guided network fuzzing framework," in *2021 18th International Conference on Privacy, Security and Trust (PST)*, 2021, pp. 1–7. DOI: 10.1109/PST52912.2021.9647801.
- [37] C. Aschermann, S. Schumilo, A. Abbasi, and T. Holz, "Ijon: Exploring deep state spaces via fuzzing," in *2020 IEEE Symposium on Security and Privacy (SP)*, 2020, pp. 1597–1612. DOI: 10.1109/SP40000.2020.00117.
- [38] V. Paliath, E. Trickel, T. Bao, R. Wang, A. Doupé, and Y. Shoshitaishvili, "Sandpuppy: Deep-state fuzzing guided by automatic detection of state-representative variables," in *Detection of Intrusions and Malware, and Vulnerability Assessment*, F. Maggi, M. Egele, M. Payer, and M. Carminati, Eds., Cham: Springer Nature Switzerland, 2024, pp. 227–250, isbn: 978-3-031-64171-8.
- [39] Y.-H. Zou, J.-J. Bai, J. Zhou, J. Tan, C. Qin, and S.-M. Hu, "TCP-Fuzz: Detecting memory and semantic bugs in TCP stacks with fuzzing," in *2021 USENIX Annual Technical Conference (USENIX ATC 21)*, USENIX Association, Jul. 2021, pp. 489–502, isbn: 978-1-939133-23-6. [Online]. Available: <https://www.usenix.org/conference/atc21/presentation/zou>.
- [40] V. J. M. Manès, S. Kim, and S. K. Cha, "Ankou: Guiding grey-box fuzzing towards combinatorial difference," in *Proceedings of the ACM/IEEE 42nd International Conference on Software Engineering*, ser. ICSE '20, Seoul, South Korea: Association for Computing Machinery, 2020, pp. 1024–1036, isbn: 9781450371216. DOI: 10.1145/3377811.3380421. [Online]. Available: <https://doi.org/10.1145/3377811.3380421>.
- [41] V.-T. Pham, M. Böhme, and A. Roychoudhury, "Affnet: A greybox fuzzer for network protocols," in *2020 IEEE 13th International Conference on Software Testing, Validation and Verification (ICST)*, 2020, pp. 460–465. DOI: 10.1109/ICST46399.2020.00062.
- [42] A. Mantovani, A. Fioraldi, and D. Balzarotti, "Fuzzing with data dependency information," in *2022 IEEE 7th European Symposium on Security and Privacy (EuroS&P)*, 2022, pp. 286–302. DOI: 10.1109/EuroSP53844.2022.00026.
- [43] S. Jero, E. Hoque, D. Choffnes, A. Mislove, and C. Nita-Rotaru, "Automated attack discovery in tcp congestion control using a model-guided approach," in *Proceedings of the 2018 Applied Networking Research Workshop*, ser. ANRW '18, Montreal, QC, Canada: Association for Computing Machinery, 2018, p. 95, isbn: 9781450355858. DOI: 10.1145/3232755.3232769. [Online]. Available: <https://doi.org/10.1145/3232755.3232769>.
- [44] Y. Hsu, G. Shu, and D. Lee, "A model-based approach to security flaw detection of network protocol implementations," in *2008 IEEE International Conference on Network Protocols*, 2008, pp. 114–123. DOI: 10.1109/ICNP.2008.4697030.
- [45] S. Gorbunov and A. Rosenbloom, "Autofuzz: Automated network protocol fuzzing framework," *Ijcsns*, vol. 10, no. 8, p. 239, 2010.
- [46] P. Zhao, S. Jiang, S. Liu, and L. Liu, "Fuzz testing of protocols based on protocol process state machines," in *2024 4th International Conference on Electronic Information Engineering and Computer Science (EIECS)*, 2024, pp. 844–850. DOI: 10.1109/EIECS63941.2024.10800590.
- [47] D. Maier, O. Bittner, J. Beier, and M. Munier, "Fitm: Binary-only coverage-guided fuzzing for stateful network protocols," Workshop on Binary Analysis Research, Internet Society, 2022. DOI: 10.14722/bar.2022.23008. [Online]. Available: <http://dx.doi.org/10.14722/bar.2022.23008>.
- [48] A. G. Voyiatzis, K. Katsigiannis, and S. Koubias, "A modbus/tcp fuzzer for testing internetworked industrial systems," in *2015 IEEE 20th Conference on Emerging Technologies & Factory Automation (ETFA)*, 2015, pp. 1–6. DOI: 10.1109/ETFA.2015.7301400.
- [49] Y. Lai, H. Gao, and J. Liu, "Vulnerability mining method for the modbus tcp using an anti-sample fuzzer," *Sensors*, vol. 20, no. 7, 2020, issn: 1424-8220. DOI: 10.3390/s20072040. [Online]. Available: <https://www.mdpi.com/1424-8220/20/7/2040>.
- [50] Z. Hu, J. Shi, Y. Huang, J. Xiong, and X. Bu, "Gan-fuzz: A gan-based industrial network protocol fuzzing framework," in *Proceedings of the 15th ACM International Conference on Computing Frontiers*, ser. CF '18, Ischia, Italy: Association for Computing Machinery, 2018, pp. 138–145, isbn: 9781450357616. DOI: 10.1145/3203217.3203241. [Online]. Available: <https://doi.org/10.1145/3203217.3203241>.
- [51] W. Wang, Z. Chen, Z. Zheng, H. Wang, and J. Luo, "MTA Fuzzer: A low-repetition rate modbus tcp fuzzing method based on transformer and mutation target adaptation," *Computers & Security*, vol. 144, p. 103973, 2024, issn: 0167-4048. DOI: <https://doi.org/10.1016/j.cose.2024.103973>. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0167404824002785>.
- [52] K. Katsigiannis and D. Serpanos, "Mtf-storm: A high performance fuzzer for modbus/tcp," in *2018 IEEE 23rd International Conference on Emerging Technologies and Factory Automation (ETFA)*, vol. 1, 2018, pp. 926–931. DOI: 10.1109/ETFA.2018.8502600.

- [53] Q. Xiong, H. Liu, Y. Xu, *et al.*, “A vulnerability detecting method for modbus-tcp based on smart fuzzing mechanism,” in *2015 IEEE International Conference on Electro/Information Technology (EIT)*, 2015, pp. 404–409. DOI: 10.1109/EIT.2015.7293376.
- [54] “Native simulator — repository.” (n.d.), [Online]. Available: https://github.com/BabbleSim/native_simulator/ (visited on Jan. 31, 2025).
- [55] “Native simulator - native.sim.” (n.d.), [Online]. Available: https://docs.zephyrproject.org/latest/boards/native/native_sim/doc/index.html (visited on Jan. 31, 2025).
- [56] “Clang documentation — addresssanitizer.” (n.d.), [Online]. Available: <https://clang.llvm.org/docs/AddressSanitizer.html> (visited on Jan. 31, 2025).
- [57] “Zephyr — repository — issue: Runtime failure on samples/net/sockets/echo with llvm 16 and asan for native.sim.” (n.d.), [Online]. Available: <https://github.com/zephyrproject-rtos/zephyr/issues/83863> (visited on Jan. 31, 2025).
- [58] A. Herrera, H. Gunadi, S. Magrath, M. Norrish, M. Payer, and A. L. Hosking, “Seed selection for successful fuzzing,” in *Proceedings of the 30th ACM SIGSOFT International Symposium on Software Testing and Analysis*, ser. ISSTA 2021, Virtual, Denmark: Association for Computing Machinery, 2021, pp. 230–243, ISBN: 9781450384599. DOI: 10.1145/3460319.3464795. [Online]. Available: <https://doi.org/10.1145/3460319.3464795>.