Efficiently Rebuilding Coverage in Hardware-Assisted Greybox Fuzzing

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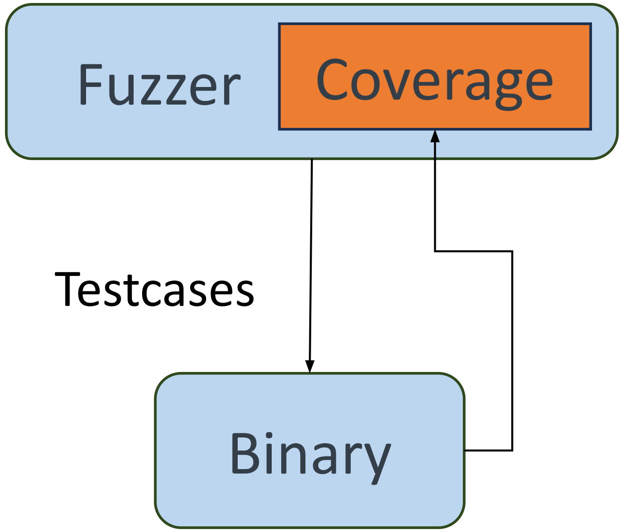
Rebuilding Coverage in Binary-only Fuzzing

Existing techniques in rebuilding coverage:

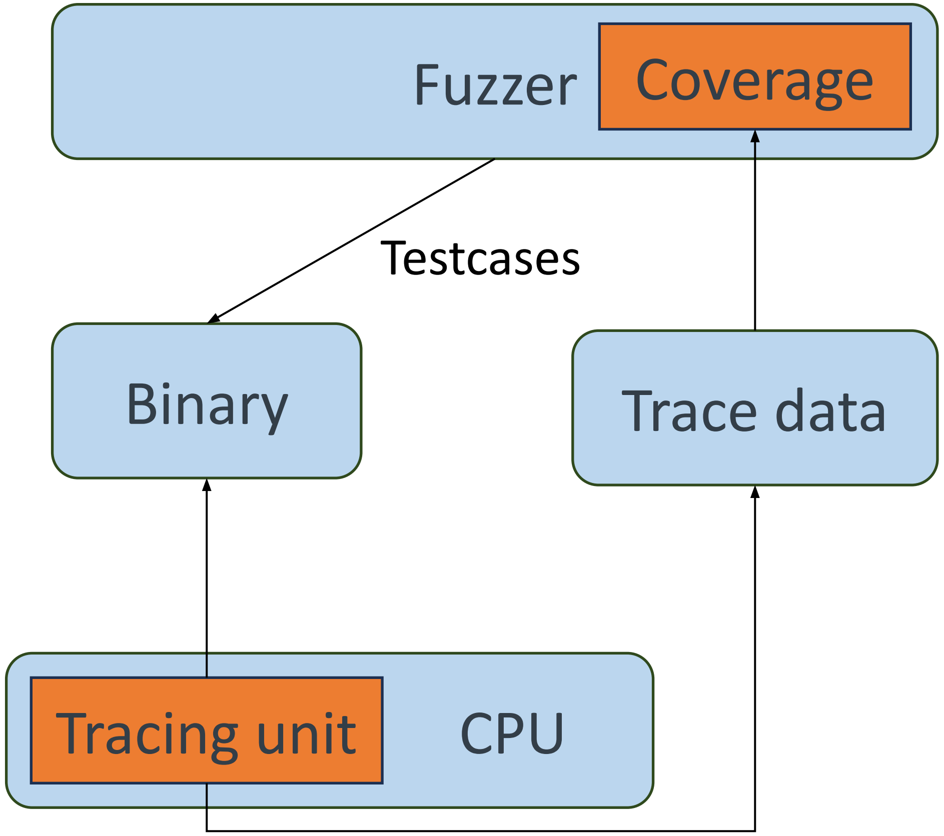
- Dynamic binary instrumentation (e.g., AFL-PIN, AFL-QEMU)
  - Heavy overhead
- Static binary rewriting (e.g., RetroWrite)
  - Additional prerequisites for binaries
- Hardware tracing (e.g., PTFuzz, PTrix)
  - Negligible runtime overhead
  - Powerful tracing ability



Hardware-assisted Greybox Fuzzing

Hardware-assisted greybox fuzzing (HGF):

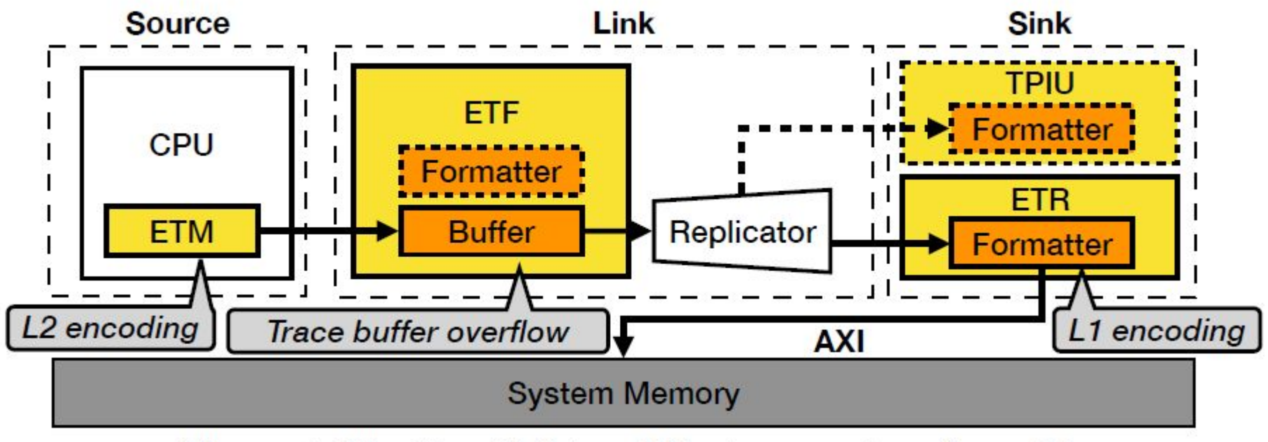
- Hardware tracing techniques (Intel PT, Arm CoreSight)
- Decoding the trace packets
- Rebuilding coverage
- Fuzzing kernel, TEE OS…



Hardware-assisted Greybox Fuzzing

Challenges in rebuilding coverage of HGF:

- **Difficult to rebuild coverage with high efficiency and moderate sensitivity**
  - Edge coverage by disassembling the binary (heavy overhead) (PTFuzz)
  - Path coverage directly from the trace packets (seed explosion) (PTrix)
  - Branch coverage by hardware features (additional decoding overhead) (μAFL)
- **Affected by the hardware tracing buffer overflow**
  - Trace data loss (imprecision and instability in coverage)



The classic architecture of CoreSight

Stalker

An efficient HGF tool based on Arm CoreSight.

Targets:

- Building moderate (branch-level) coverage with low overhead to avoid the seed explosion
- Alleviating the trace buffer overflow

Methods:

- Double-layer coverage mechanism
- Adaptive CPU frequency modulation mechanism (ACFMM)

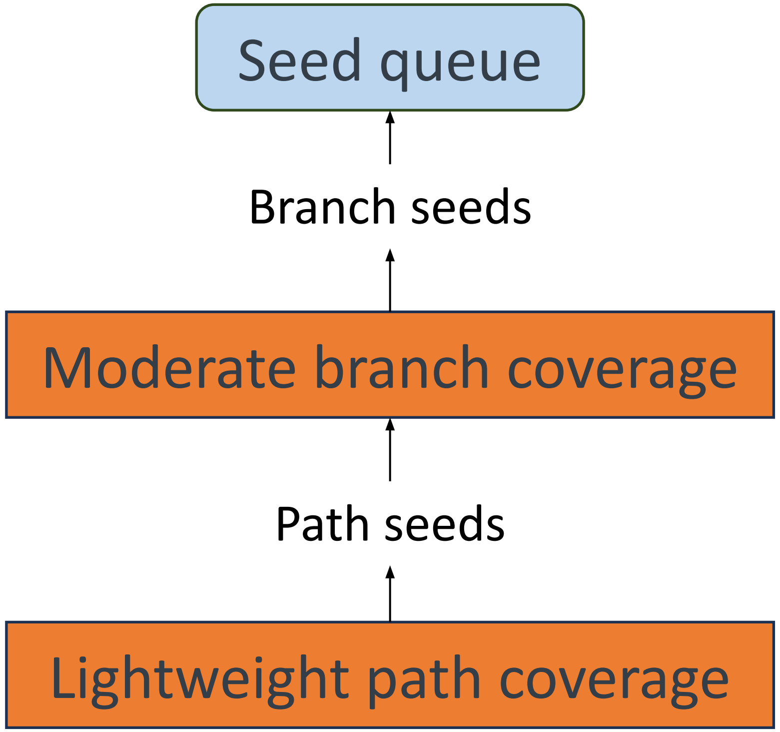
Double-layer Coverage Mechanism

Stalker utilizes this mechanism to efficiently rebuild coverage and select the seeds in moderate coverage.

Key point: assigning the execution of test cases and the selection of seeds to different coverages.

Details:

- Lightweight path coverage in bottom layer
- Moderate branch coverage in top layer



Double-layer Coverage Mechanism

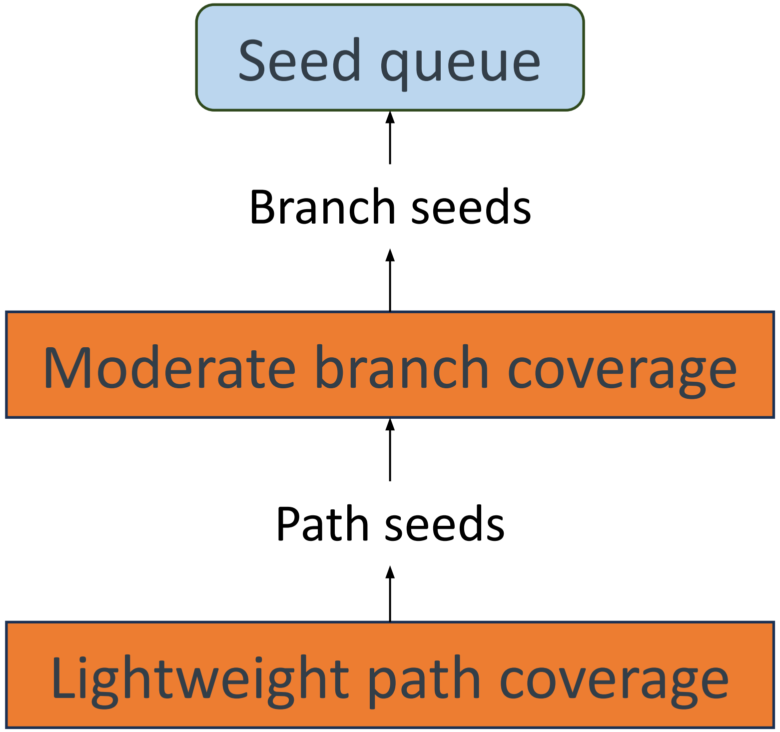
Stalker rebuilds these coverages by directly decoding the trace packets without disassembling the binaries.

Lightweight path coverage: efficiently executing the testcases and selecting the path seeds.

- ETM default mode
- Sensitive coverage (seed explosion)

Moderate branch coverage: effectively filtering the path seeds and selecting and adding the branch seeds into the seed queue.

- ETM Branch Broadcasting (BB) mode
- Additional decoding overhead



Double-layer Coverage Mechanism

Stalker also implements many strategies for efficiently and stably rebuilding coverage.

Branchless design: accelerate rebuilding coverage

Filtering noisy packets: keeping the stability of coverage

Disable formatter: reducing the decoding overhead

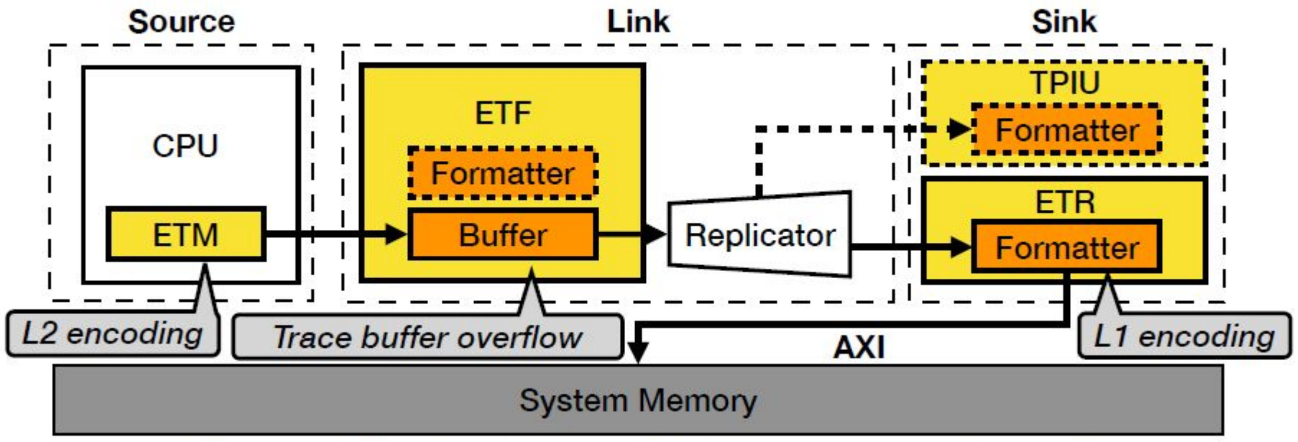
Adaptive CPU Frequency Modulation Mechanism

Stalker utilizes the ACFMM to maintain a high CPU frequency and alleviate the trace buffer overflow.

Key observation: slowing down the CPU frequency can decrease the ETM bandwidth

Key point:

- If there is frequent buffer overflow over time, reducing the CPU frequency to prevent overflow
- When no overflow occurs for an extended period, the frequency is increased to accelerate execution



The classic architecture of CoreSight.

Adaptive CPU Frequency Modulation Mechanism

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Algorithm 4 ACFMM

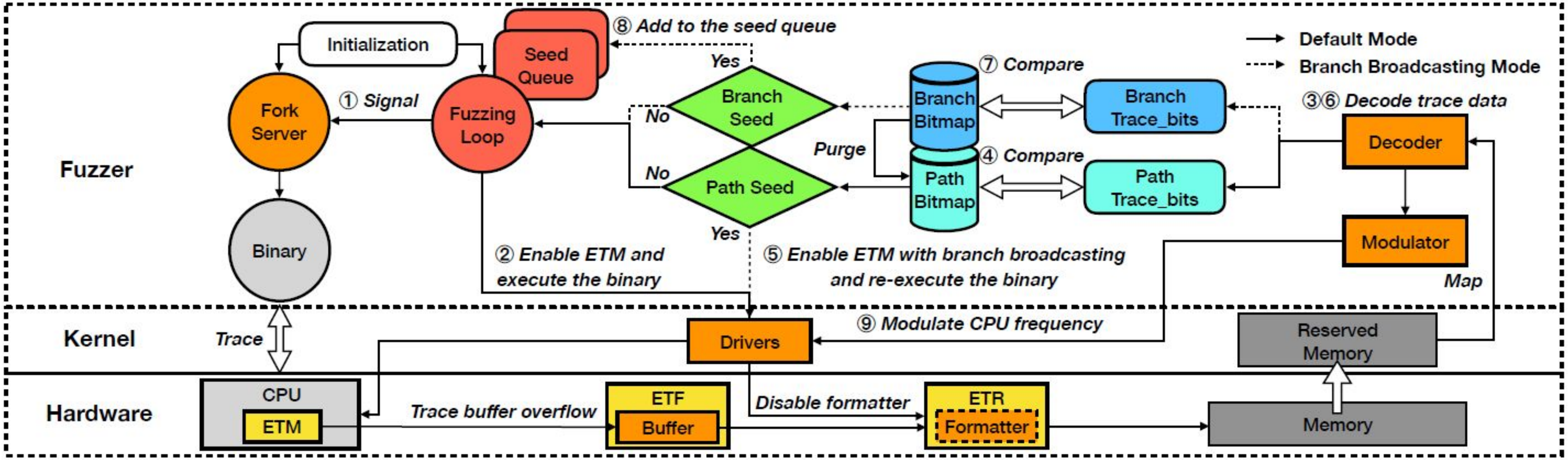
```
repeat
    testcase = Mutation(seed)
    overflow_flag = RunTarget(COV, testcase)
    if COV == PATH_COV then
        path_execs += 1
    end if
    if overflow_flag == TRUE then
        if COV == PATH_COV then
            overflow_nums_path += 1
        end if
        no_overflow_num = 0
        Decrease(cur_cpu_freq_mode)
    else
        no_overflow_num += 1
        if no_overflow_num == INTERVAL then
            Increase(cur_cpu_freq_cov)
            no_overflow_num = 0
        end if
    end if
    INTERVAL = (path_execs / overflow_nums_path) / 5
    Limit(INTERVAL)
until fuzzer exit
```

The algorithm of ACFMM.

Stalker

Stalker is built on AFL and Arm CoreSight.

- Implementing the forkserver
- Optimizing the CoreSight driver and decoder



The architecture and workflow of Stalker

Experiments Setup

Platform: Arm Juno R2 development board
(A72*2 0.6-1.2GHz, A53*4 0.45-0.95GHz)

Compare tools:

- QEMU-based: AFL-QEMU, AFL-QEMU++[1]
- CoreSight-based: Armored-CoreSight, μAFL
- PT-based: PTrix, libxdc (kAFL)

Tested software:

- 10 real-world programs selected from other papers in top conferences
- Benchmark of libxdc

Table 1: Target binaries evaluated in our evaluation.

Program	Version	Size	Format
objdump –dwarf-check -C -g -f -dwarf -x @@	binutils-v2.37	11MB	elf
readelf -a @@	binutils-v2.37	4MB	elf
nm-new -C @@	binutils-v2.37	5.8MB	elf
bsdtar -xf @@ /dev/null	libarchive-3.5.2	3.4MB	tar
nasm -f elf -o sample @@	nasm-2.15.05	3.0MB	text
bison @@	bison-3.8	2.6MB	text
tiff2bw @@ /dev/null	tiff-4.3.0	1.5MB	tiff
tiffinfo @@	tiff-4.3.0	1.6MB	tiff
xmllint @@	libxml2-2.9.10	100KB	xml
tic @@	ncurses-6.3	260KB	text

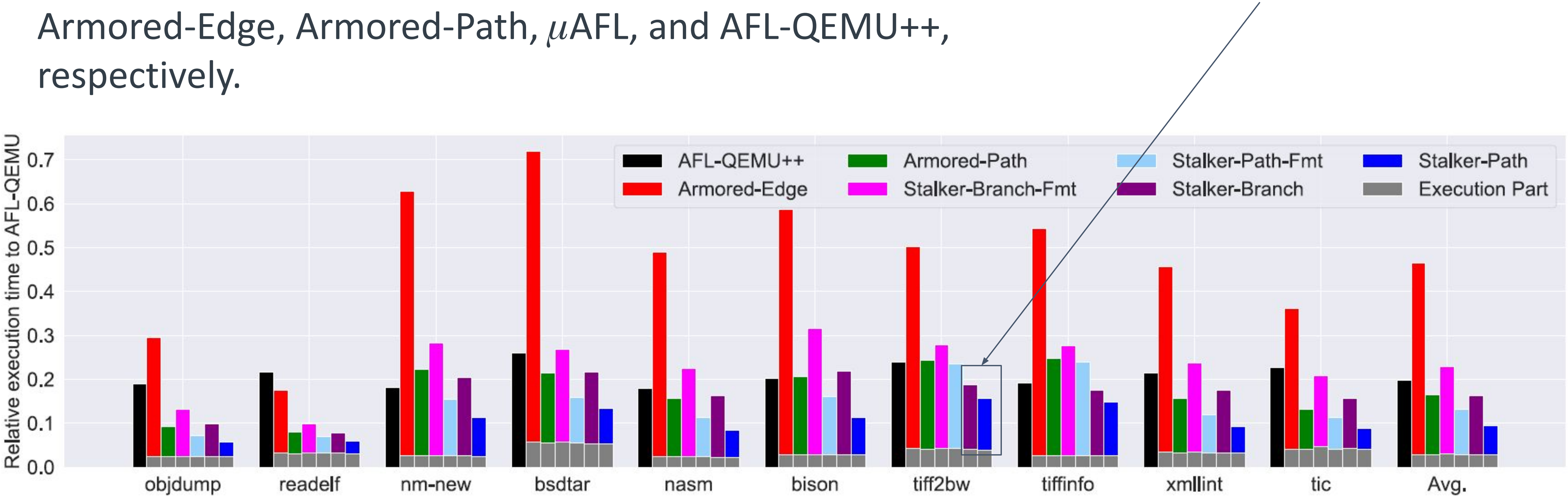
The real-world programs in our evaluation

[1] https://abiondo.me/2018/09/21/improving-afl-qemu-mode/

Efficiency of Rebuilding Coverage

Compared with CoreSight-based and QEMU-based tools:
Stalker rebuilds the same granularity coverage more efficiently, with 2.81×, 1.74×, 1.4×, and 1.22× faster than Armored-Edge, Armored-Path, μAFL, and AFL-QEMU++, respectively.

Branch coverage and path coverage of Stalker

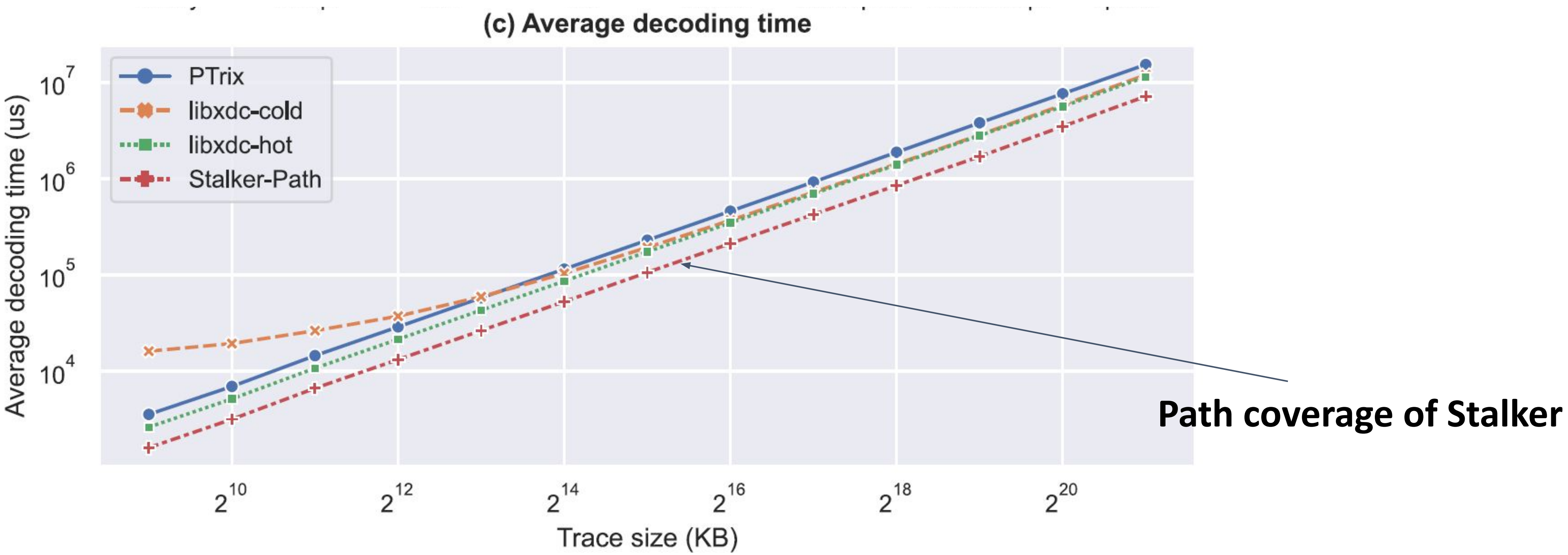


Normalized execution time of all tools with AFL-QEMU as the baseline

Efficiency of Rebuilding Coverage

Compared with PT-based tools:

Stalker-Path outperforms PTrix and libxdc by 2.2× and 1.63×, respectively.

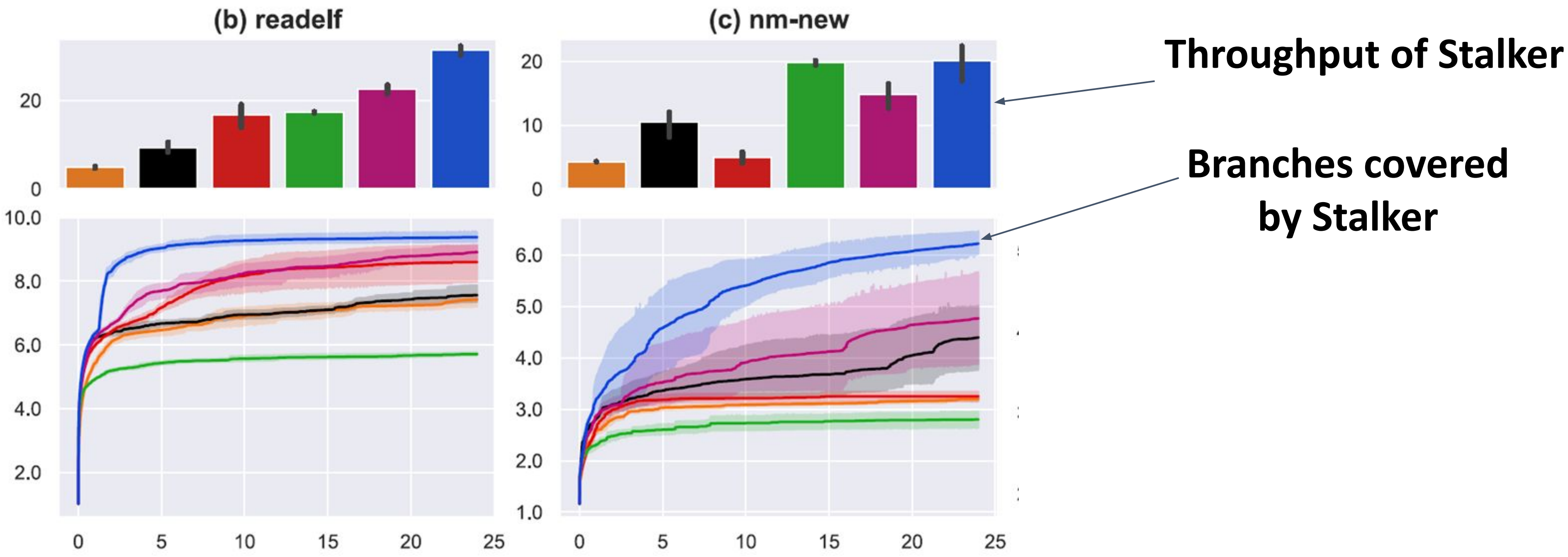


Decoding time of PTrix, libxdc-cold, libxdc-hot, and Stalker-Path on different trace file sizes

Performance of Stalker

Results:

On 10 programs, Stalker surpasses AFL-QEMU, AFL-QEMU++, Armored-Edge, Armored-Path, and μAFL with higher throughput and covering 55.7%, 13.7%, 66.4%, 323.3%, and 19.2% more paths and 21.1%, 10.0%, 23.9%, 66.1%, and 3.5% branches, respectively.



Throughput and branch coverage of six tools over 24 hours. The blue line represents Stalker.

Double-Layer Coverage Mechanism

Metrics: counting the number of seeds before and after the filtering as N_q and N_f, defined the sensitive ratio as N_q/N_f.

Results:

- Improving the speed of Stalker as executing 86.7% test cases with lightweight coverage
- Filtering 6,124 branch seeds from the 1.62M path seeds and adding them into the queue
- The sensitivity of branch coverage in Stalker is comparable to that of the branch-count coverage

Path seeds   Branch seeds

Table 3: Numbers of selected and filtered seeds of the hardware-assisted tools, respectively. The right column denotes the number of seeds filtered by AFL in the branch-count coverage. The two left columns in STALKER, and one in others represent the number of seeds selected by them.

Binary	Armored-Edge	Armored-Path	STALKER-Branch-Fmt	STALKER (Path Seed/Branch Seed)
objdump	8,820/5,277	51.55K/2,199	9,850/7,627	0.42M/10.63K/8,476
readelf	9,271/6,358	67.05K/1,715	9,335/6,639	1.54M/10.4K/7,345
nm-new	3,202/1,058	56.24K/591	3,781/2,478	0.35M/7,576/4,850
bsdtar	5,750/1,701	64.91K/193	3,034/1,879	4.75M/3,225/2,043
nasm	4,156/1,706	83.29K/1,279	7,324/4,477	0.48M/8,164/4,889
bison	3,367/805	66.16K/814	3,388/2,197	1.11M/3,627/2,282
tiff2bw	2,924/1,377	60.17K/547	2,371/1,717	2.12M/2,566/1,842
tiffinfo	4,135/2,152	59.86K/626	3,353/2,295	1.93M/3,513/2,422
xmllint	6,641/2,598	0.2M/1,192	5,221/3,021	2.18M/5,509/3,115
tic	5,164/2,163	0.26M/753	5,330/2,843	1.28M/6,032/3,118
Avg.	5,343/2,519	97.37K/990	5,298/3,517	1.62M/6,124/4,038
N_q/N_f	212%	9835%	151%	26392%/152%

The number of seeds before and after the filtering.

Sensitive ratio

Adaptive CPU Frequency Modulation Mechanism

Effectiveness of ACFMM:

- Achieving the highest coverage with ACFMM
- Reducing the overflow percentage from 40.92% to 2.46%

Table 5: Average branches, number of branch and path seeds (B/P seeds), throughput, and overflows of STALKER, STALKER-A72-0.6GHz, and STALKER-A72-1.2GHz on nasm. Numbers in the brackets of Throughput: percentages of the test cases executed under 0.6GHz, 1.0GHz, and 1.2GHz.

Config	Branch	B/P Seeds	Throughput(0.6/1.0/1.2)	Overflow
ACFMM	5,649	9,202/890K	3.93M(58%/22%/21%)	96,909(2.46%)
A72-0.6GHz	5,435	8,465/507K	2.23M(100%/-/-)	0.23M(10.34%)
A72-1.2GHz	5,188	22,073/1.17M	4.12M(-/-/100%)	1.68M(40.92%)

The results of disabling/enabling the ACFMM.

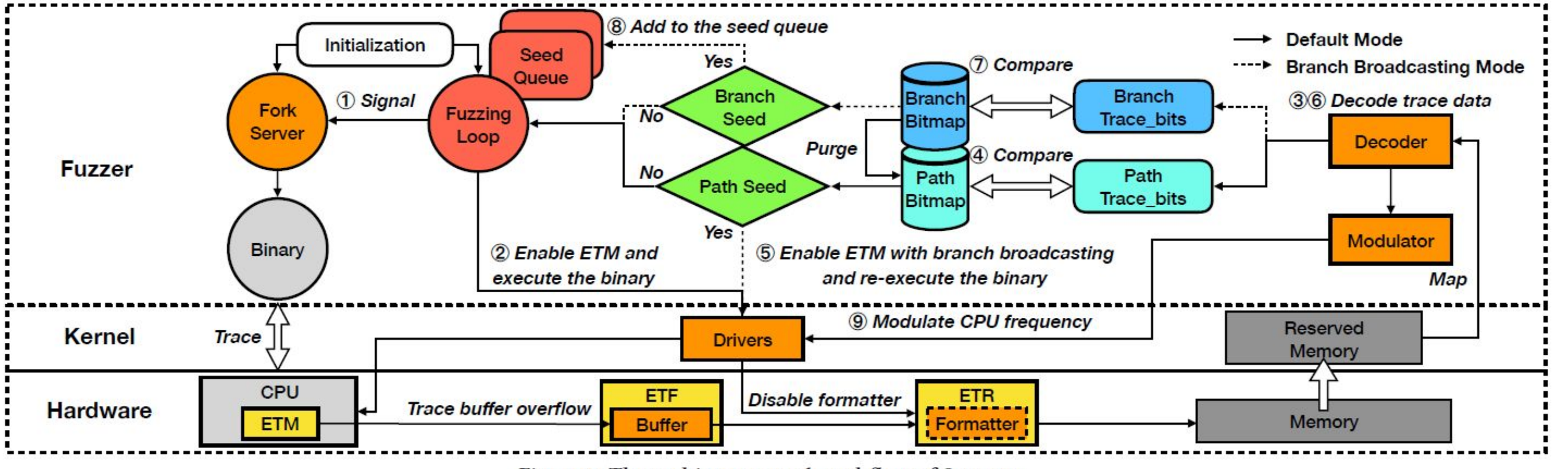
Branches covered by Stalker

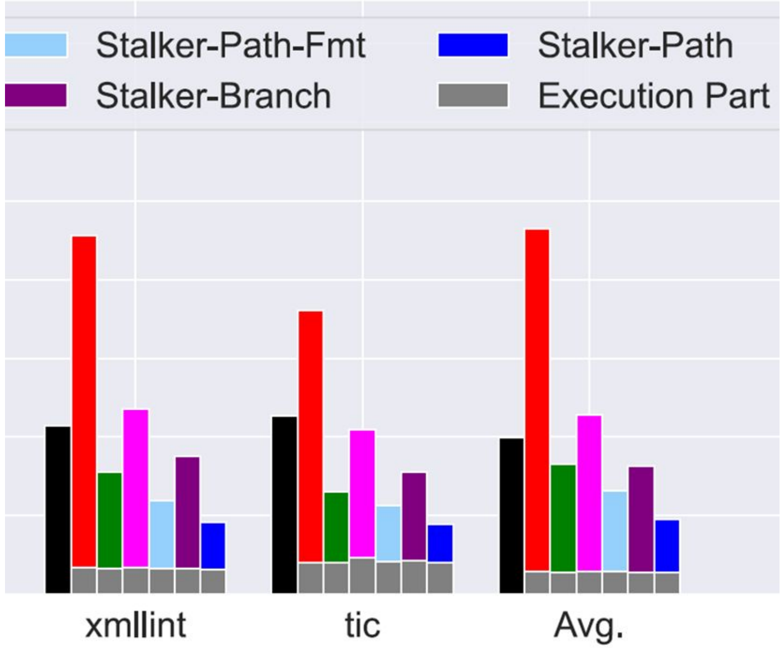
Percentage of overflow testcases

Conclusion

Stalker: an efficient hardware-assisted greybox fuzzer based on Arm CoreSight.

- Double-layer coverage mechanism
- Adaptive CPU frequency modulation mechanism





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