RAP-Track: Efficient Control Flow Attestation via Parallel Tracking in Commodity MCUs

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62 THE CHIPS TO SYSTEMS CONFERENCE

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Introduction

- Low-cost, energy efficient MCUs

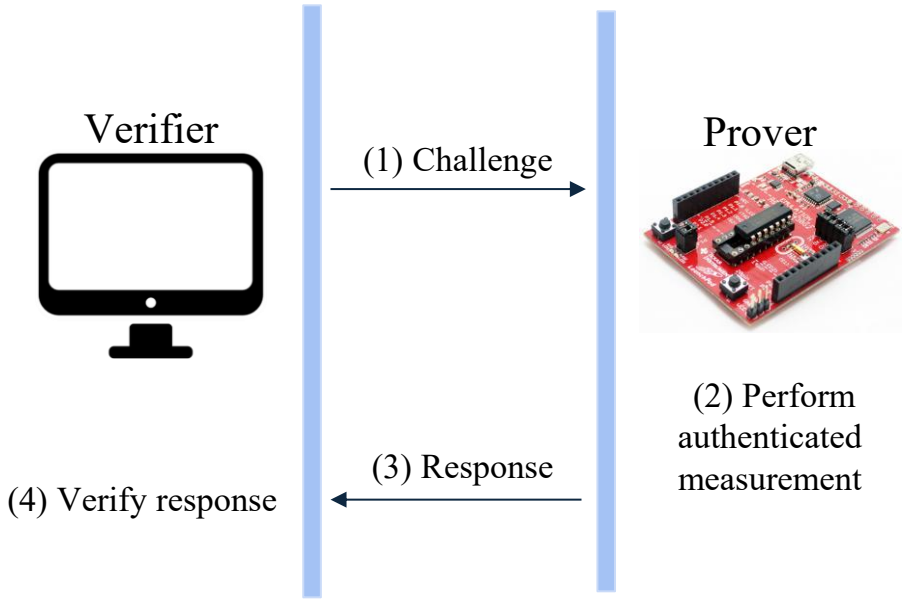
  - Limited processing power, memory size, memory protection, etc ..

- Resource constrained impact security features

- Execute safety-critical tasks in modern systems

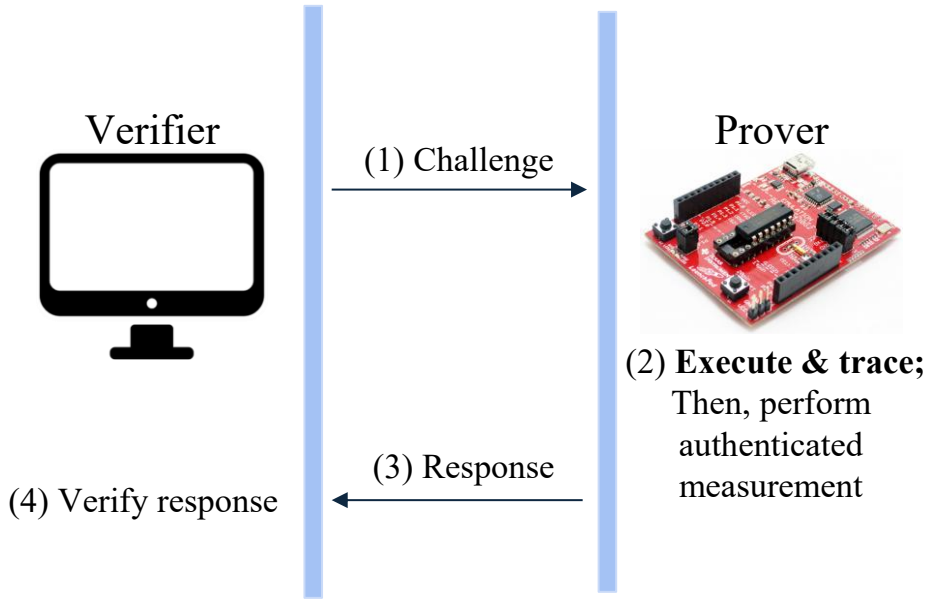
Remote Attestation

- A security mechanism designed to verify the integrity of remote device
- Ensures that the device's software state is untampered and operating as expected.
- Challenge and response protocol



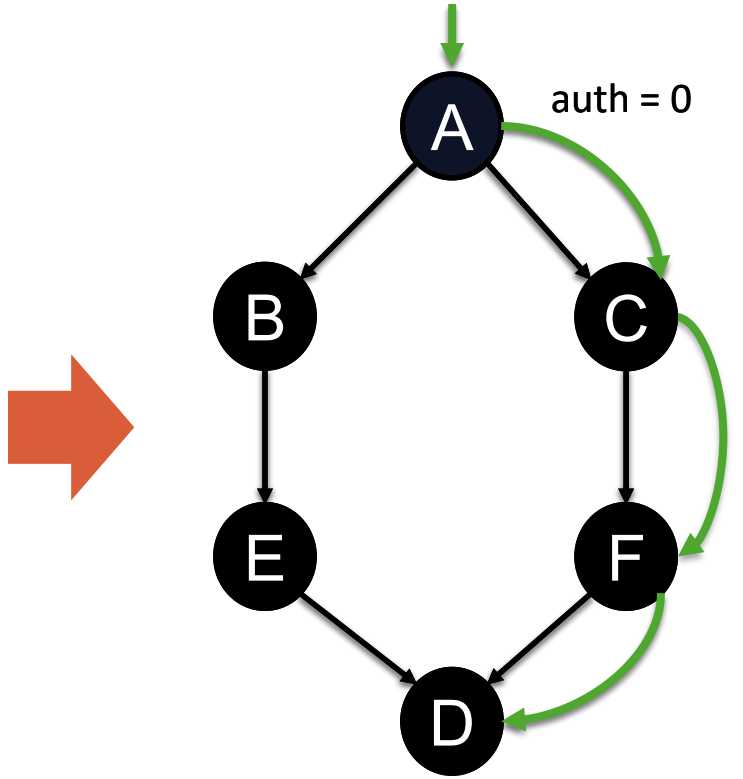
Control Flow Attestation (CFA)

- CFA extends RA to provide proof of runtime behavior of the application
- Prover records a trace of the control flow transfers (branches) during execution
- The trace and memory are measured to obtain proof about both static and runtime states



Control Flow Attestation (CFA)

```
A  if (auth)
B       do   function1();
C       else function2()
D  end
E  def function1(){…}
F  def function2(){…}
```



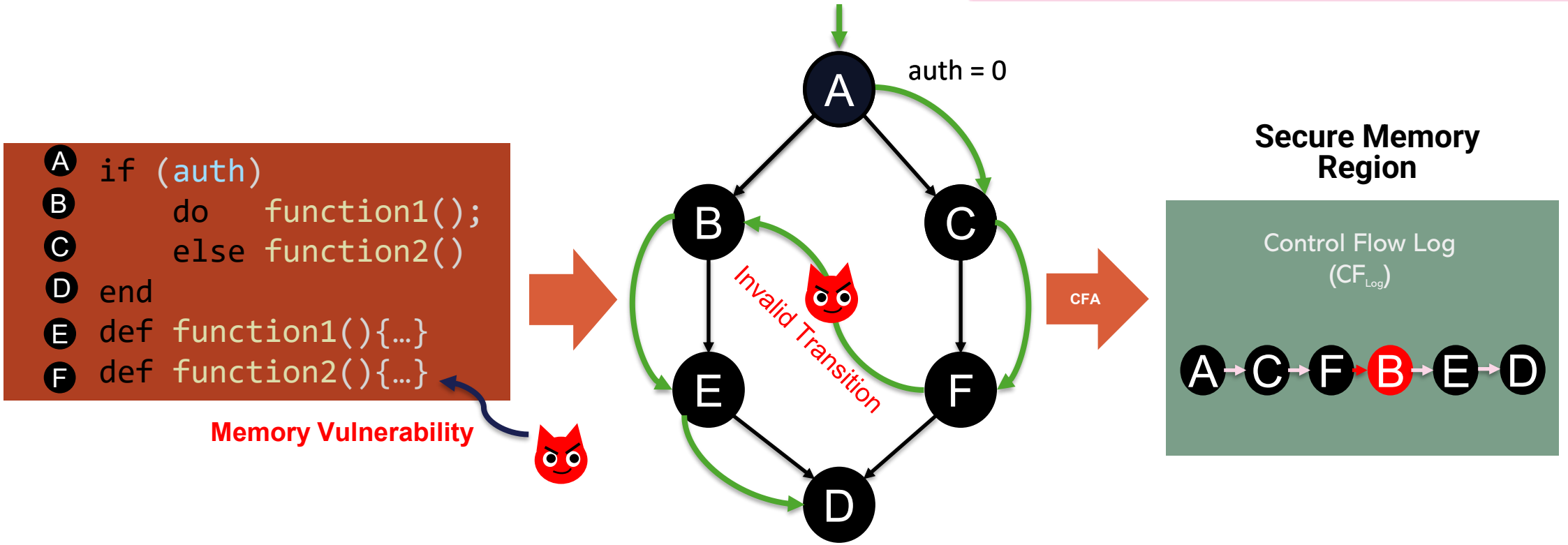
CFA

Secure Memory Region

Control Flow Log (CF_{Log})

A → C → F → D

Control Flow Attestation (CFA)



CFA Approaches

Instrumentation + Trusted Software

- Use binary instrumentation to prepend/replace branch instructions in the attested app with *trampoline* instructions
- These instructions *trampoline* into a trusted software region
- The trusted software logs the branch destination then returns
- **Problems:**
  - Significant overheads to application run-time
  - Significant increase in application binary size

CFA Approaches

Tracing Hardware (custom or commodity)

- Dedicated hardware module that detects and logs control flow transfers
- Can operate in parallel to the attested code
- No run-time overhead
- **Problems:**
  - Custom hardware: not immediately deployable
  - Commodity (relatively new!) :
    - General purpose
    - Records redundant data and overflows quickly

Micro Trace Buffer (MTB)

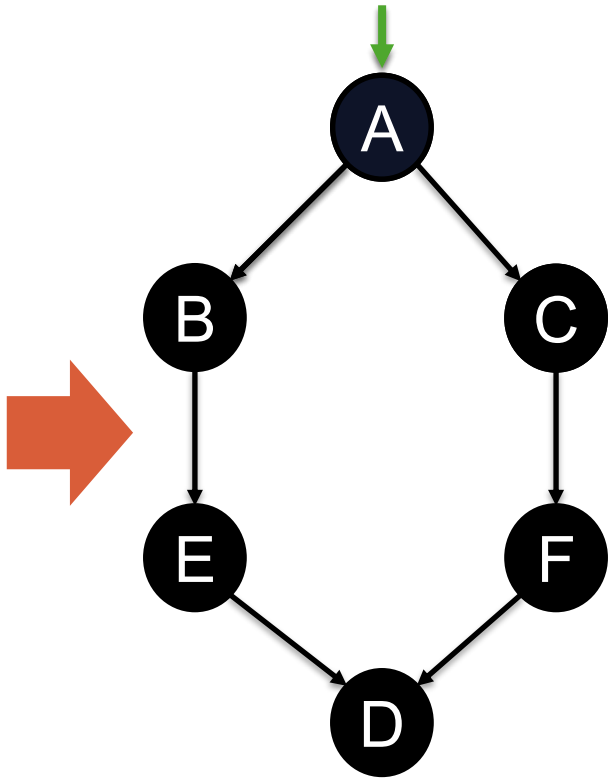
- A lightweight on-chip control flow tracing (available in ARM MCUs)

Key Features:

- Circular buffer in RAM for storing memory address values
- When activated**, records all changes in program flow** where the Program Counter does not increment sequentially.
  - **Function calls**, **branches**, and **interrupts**.
- Records the source and destination of instructions that break sequential execution

Micro Trace Buffer (MTB)

```
0x01  A  if (auth)
0x02  B      do function1();
0x03  C      else function2()
0x04  D  end
0x05  E  def function1(){…}
0x06  F  def function2(){…}
```

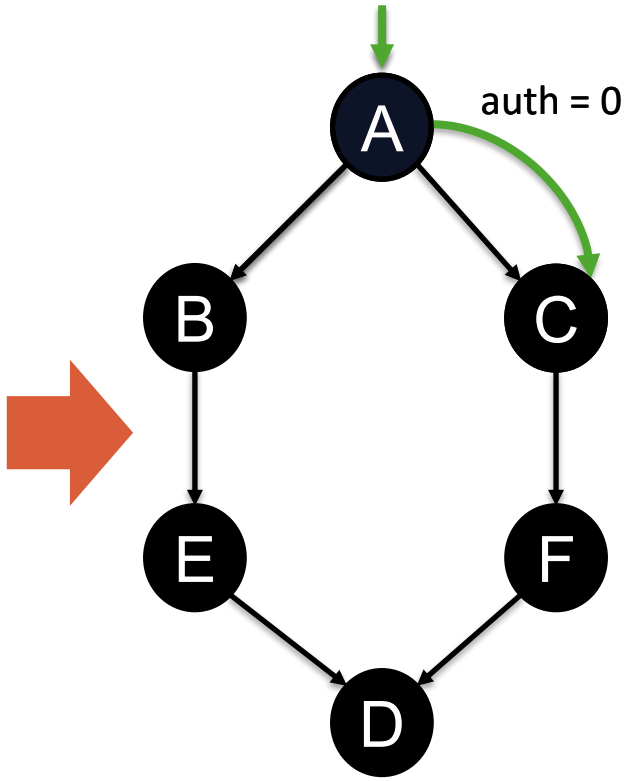


MTB

Source	Dest.

Micro Trace Buffer (MTB)

```
0x01  A  if (auth)
0x02  B      do function1();
0x03  C      else function2()
0x04  D  end
0x05  E  def function1(){…}
0x06  F  def function2(){…}
```



MTB

Source	Dest.
0x01	0x03

Micro Trace Buffer (MTB)

```
0x01  A  if (auth)
0x02  B      do function1();
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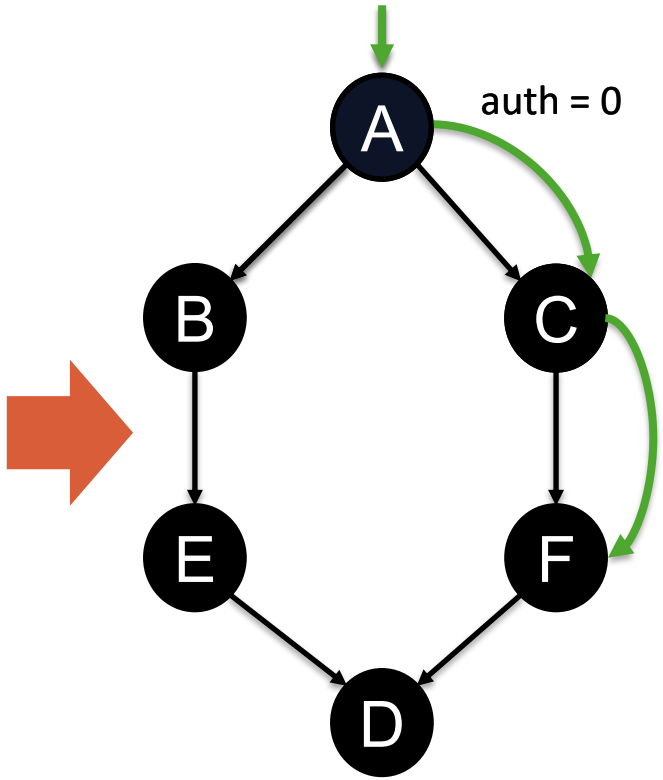
```



MTB

Source	Dest.
0x01	0x03
0x03	0x06

Micro Trace Buffer (MTB)

```
0x01  A  if (auth)
0x02  B      do function1();
0x03  C      else function2()
0x04  D  end
0x05  E  def function1(){…}
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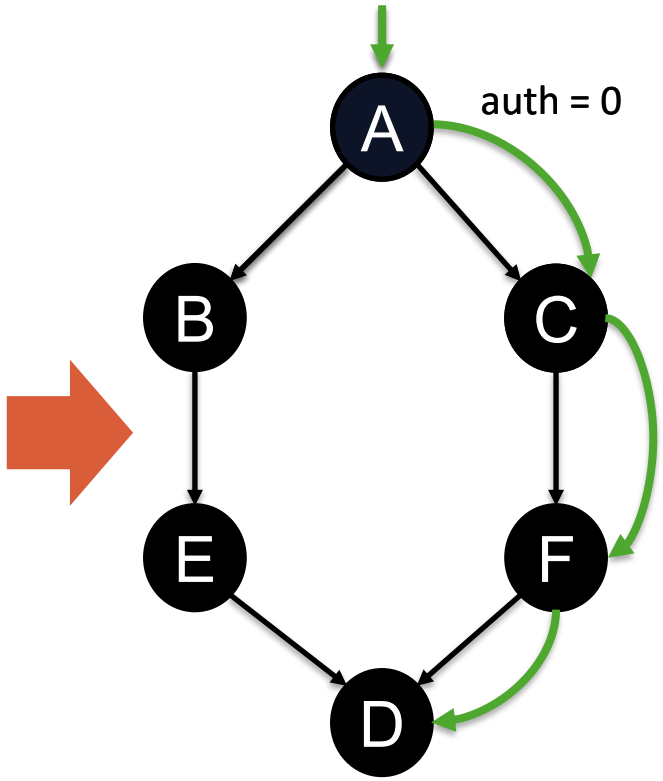
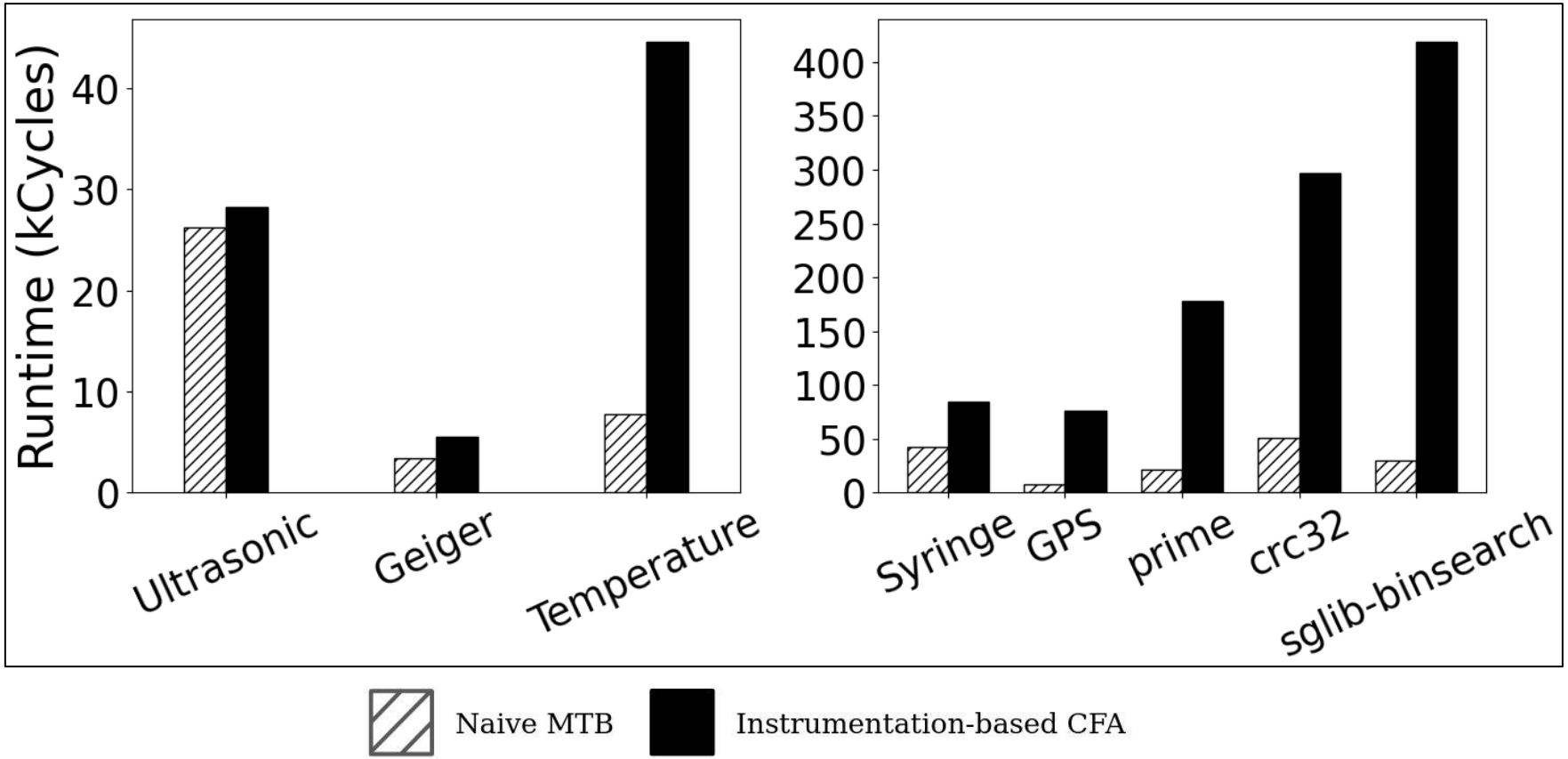


MTB

Source	Dest.
0x01	0x03
0x03	0x06
0x06	0x04

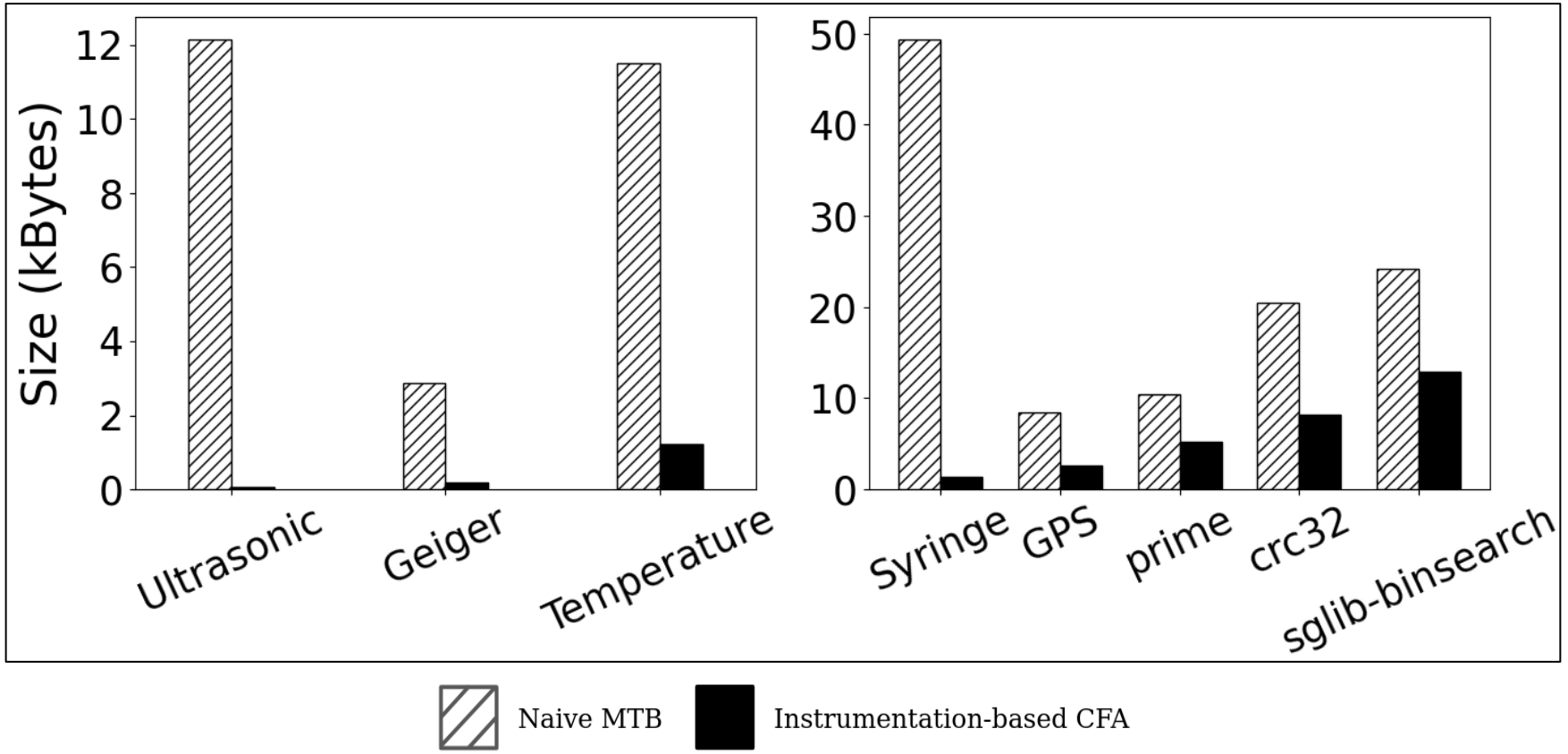
Problems of CFA Quantified

Instrumentation-based approaches incur significant run-time overheads (1.9-217x larger)



Problems of CFA Quantified

CF_{Log} cannot be optimized as easily in naïve MTB use, risking overflows or interrupts for transmission



RAP-Track

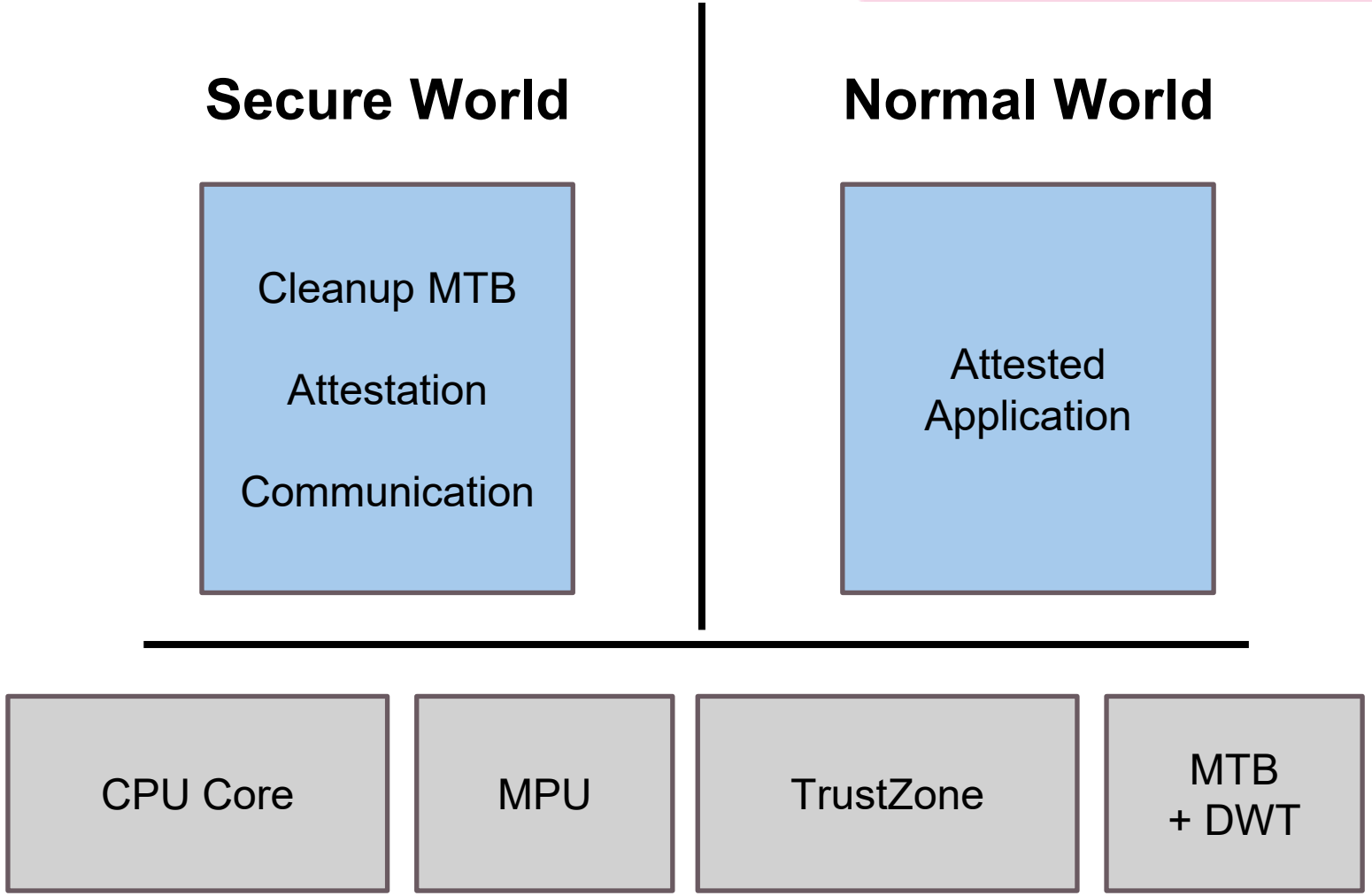
Key Idea:

- RAP-Track customizes the use of ARM's MTB and Data Watchpoint and Trace (DWT) for low-overhead control flow attestation (CFA).
- Strategic linking and static analysis to so MTB only records non-deterministic branches

Efficiency Gains:

- Fewer Secure World calls via buffered trace updates (MTB)
- Excludes deterministic/redundant branches from logs
- Reduces runtime and storage overhead

Depiction

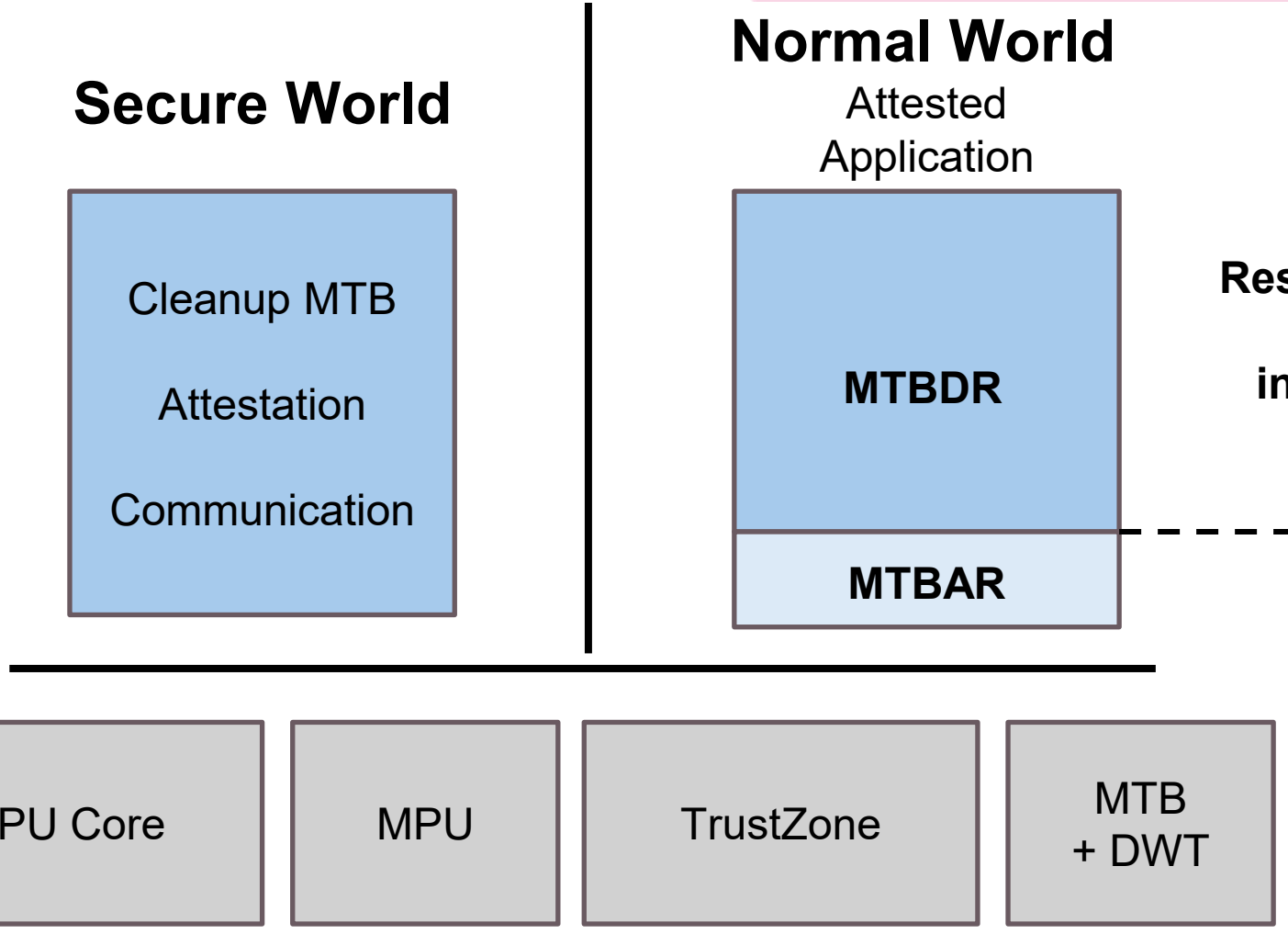

Secure World
Normal World
Cleanup MTB
Attestation
Communication
Attested Application
CPU Core
MPU
TrustZone
MTB + DWT

Depiction

Split application into two fixed regions:

MTB Activation Region (MTBAR)

MTB Deactivation Region (MTBDR)



Restructure binary so only relevant instructions are in MTBAR

MTBAR and MTBDR

MTBAR – *MTB Activation Region*

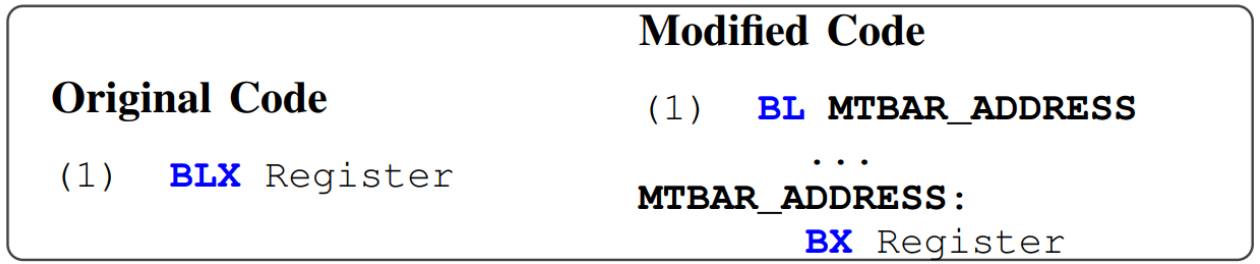
•Contains **non-deterministic branches**:
- Indirect calls
- Returns
- Conditional branches with variable outcomes

MTBDR – *MTB Deactivation Region*

•Contains **deterministic code paths**:
- Fixed branches
- Simple, statically analyzable loops

Trampoline Logic

- Rewrites indirect and conditional branches using trampolines
- Trampolines redirect to monitored regions (MTBAR)
- Ensures only essential control-flow transitions are logged



Example: Indirect call

Trampoline Logic

Original Code	Modified Code

`POP {PC}`	`B MTBAR_POP_ADDR`
	`...`
	`MTBAR_POP_ADDR:`
	`  POP {PC}`

Original Code	Modified Code

`LDR PC, [sp, #4]`	`B MTBAR_LDR_ADDR`
	`...`
	`MTBAR_LDR_ADDR:`
	`  LDR PC, [sp, #4]`

Returns and Indirect Jumps

Trampoline Logic

Original Code

```
     CMP R0,#0
(1)  BEQ taken_address
```

Modified Code

```
     CMP R0,#0
(1)  BEQ MTBAR_ADDRESS
       ...
MTBAR_ADDRESS:
     B taken_address
```

Non-loop conditional branch

Trampoline Logic

Original Code

```
loop_start:
      ...
      CMP R0,#0
(1)   BEQ loop_start
```

Modified Code

```
loop_start:
      ...
      CMP R0,#0
(1)   BEQ MTBAR_ADDRESS
      ...
MTBAR_ADDRESS:
      B loop_start
```

“Backward” loop conditional branch

Original Code

```
      CMP R0,#0
      BEQ loop_end
      ADD R1, R2, R3
      ...
loop_end:
      ...
```

Modified Code

```
      CMP R0,#0
      BEQ loop_end
(1)-> B MTBAR_ADDRESS
br_not_taken_addr:
      ADD R1, R2, R3
      ...
loop_end:
      ...
MTBAR_ADDRESS:
      B br_not_taken_addr
```

“Forward” loop conditional branch

+Plus, additional instrumentation for simple-loop optimizations

Evaluation

Setup:

- Implemented on V2M-MPS2-0318C FPGA board
- Based on ARM Cortex-M33 (v8) with TrustZone, MTB, and DWT

Code Footprint:

- Secure World size: 11 KB total
  - CFA Engine: 2.8 KB

Static analysis:

- Combination of python and bash scripts
- Operates directly on executables
- Uses ELFtools, Keystone

Evaluation

Compare RAP-Track to two CFA implementations:

Naïve MTB – using the MTB without any consideration for redundancy

TRACES – instrumentation-based CFA in ARM Cortex-M MCUs

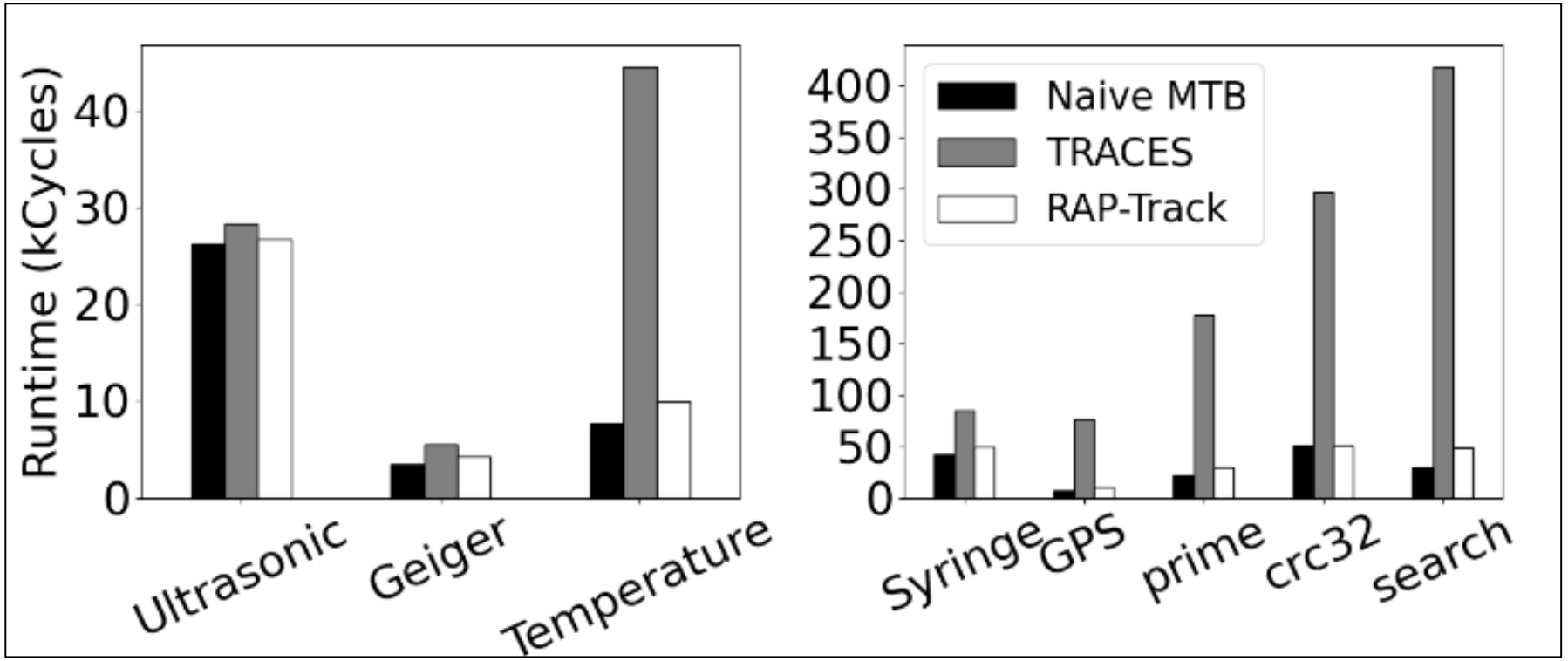
Evaluate by measuring:

- Application runtime
- CFLog size
- Code size

Evaluation

Runtime Analysis:

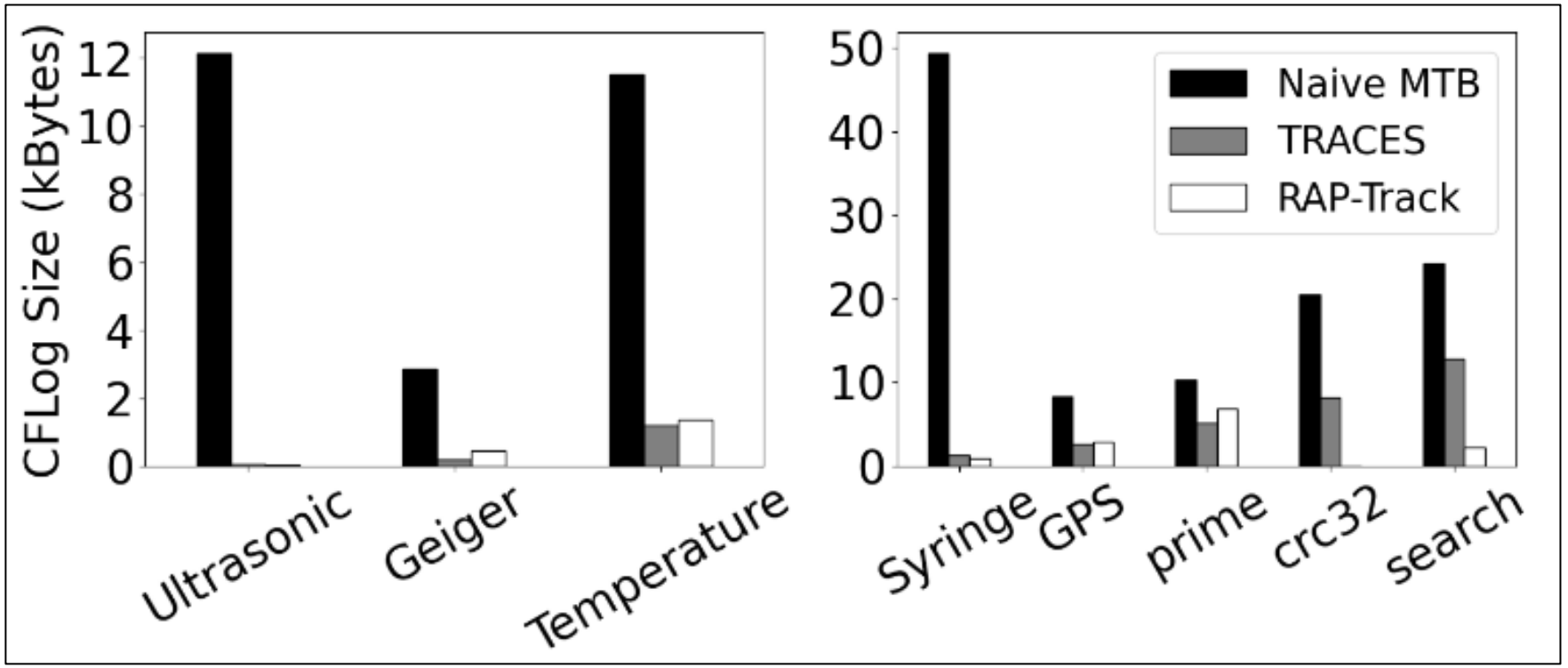
- RAP-Track has similar overhead as naïve MTB
- Compared to TRACES it reduces runtime overhead by **5.26%-88.4%**



Evaluation

CF_{Log} size:

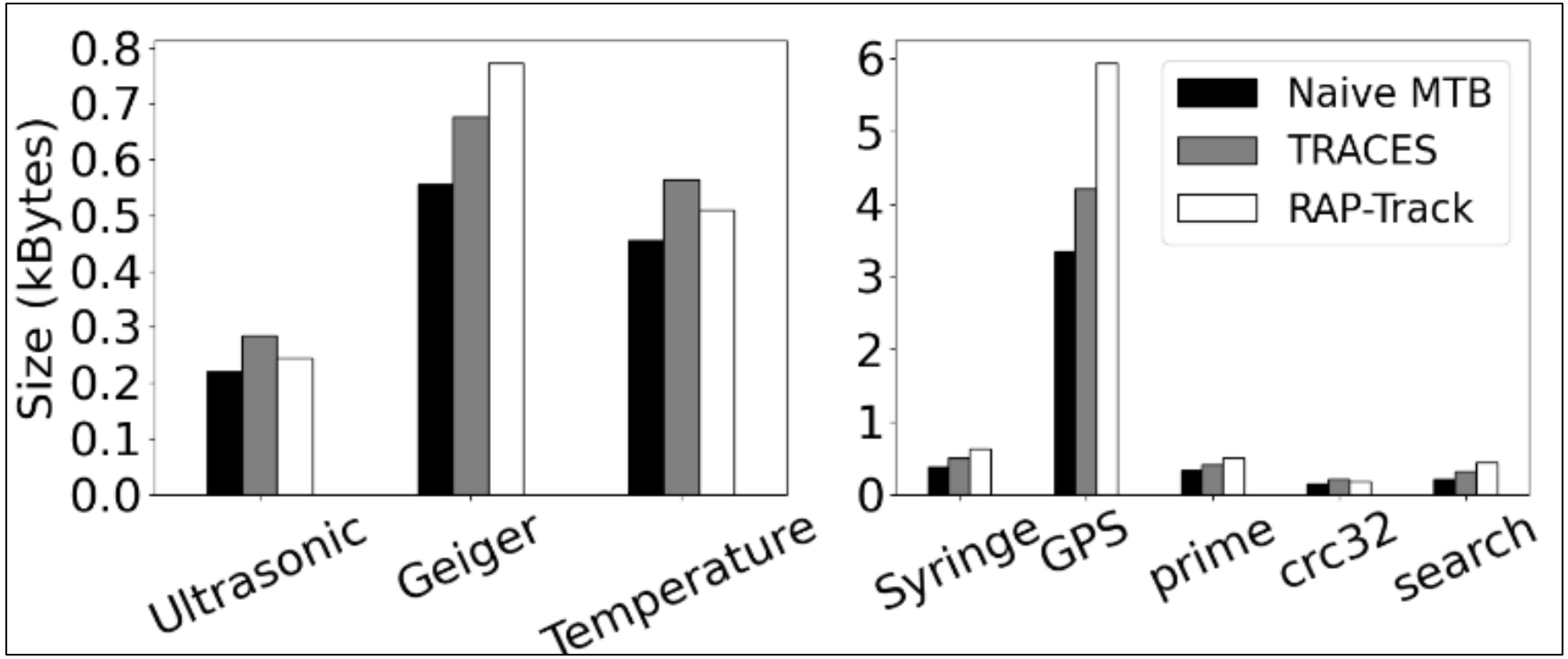
- RAP-Track reduces total recorded data from naïve MTB by **33.3-99.9%**
- Comparable results to TRACES (with software optimizations)



Evaluation

Code Size:

- RAP-Track always increased code size compared naïve MTB (**10.9-108%**)
- Code size compared to TRACES depends on the application
  - Could increase (**up to 41.5%**) or decrease (**up to 14.1%**)
- The savings for other factors (**up to 99.9% for CF_{Log}**, **up to 88.4% for runtime**) are more impactful



Conclusion

- RAP-Track enables efficient, lossless CFA for embedded systems
- Leverages existing hardware – no need for custom chips
- Provides reasonable tradeoff between performance and memory usage