BenchIoT: A Security Benchmark for The Internet of Things

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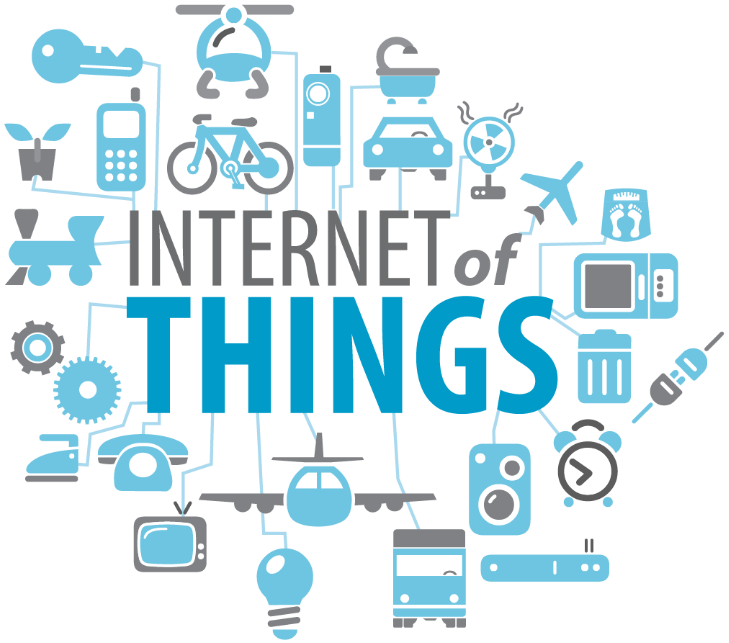
Internet of Things

- **The number of IoT devices is expected to exceed 20 billion by 2020.**

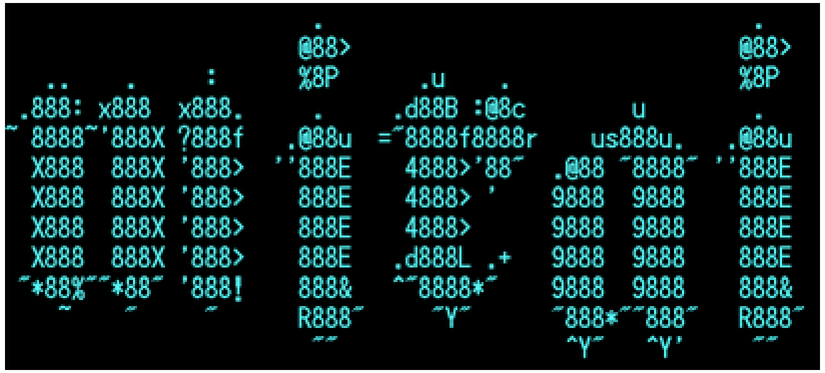
- **Many will be microcontroller based systems (IoT-µCs).**
  - Run single static binary image directly on the hardware.
  - Can be with/without an OS (bare-metal).
  - Direct access to peripherals and processor.
  - Small memory.



- **Examples:**
  - WiFi System on Chip
  - Cyber-physical systems
  - UAVs

Internet of Things Security

- In 2016, one of the largest DDoS attack to date was caused by IoT devices[1].



- In 2017, Google's Project Zero used a vulnerable WiFi SoC to gain control of the application processor on smart phones[2].

[1] https://krebsonsecurity.com/2016/09/krebsonsecurity-hit-with-record-ddos/
[2] https://googleprojectzero.blogspot.co.uk/2017/04/over-air-exploiting-broadcoms-wi-fi_4.html

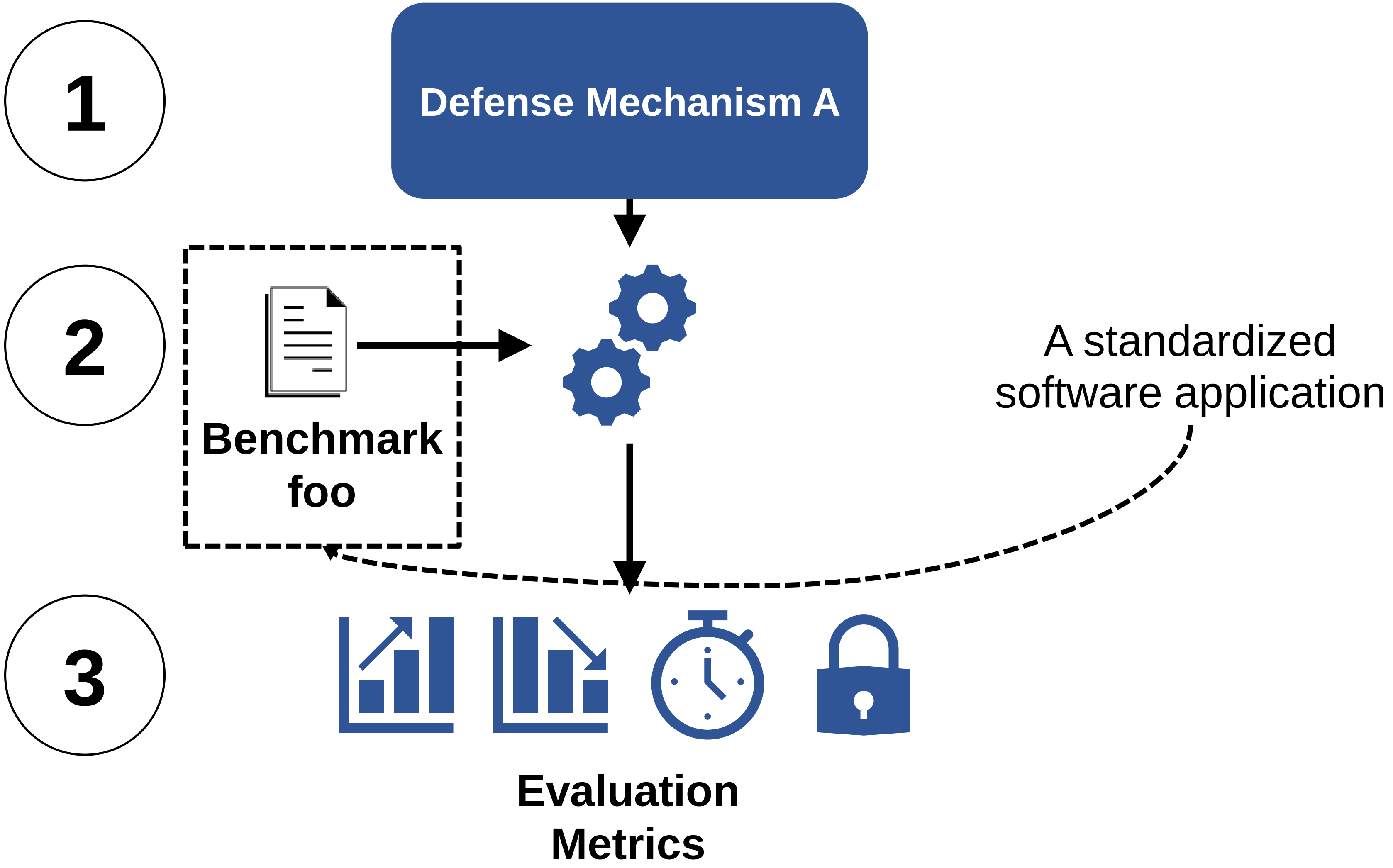
Evaluation in Current IoT Defenses

- **Multiple defenses have been proposed.**
  - TyTan[DAC15], TrustLite[EurSys14], C-FLAT [CCS16], nesCheck[AsiaCCS17], SCFP[EuroS&P18], LiteHAX[ICCAD18] CFI CaRE [RAID17], ACES[SEC18], MINION [NDSS18], EPOXY [S&P17]
- **How are they evaluated?**
  - Ad-hoc evaluation.

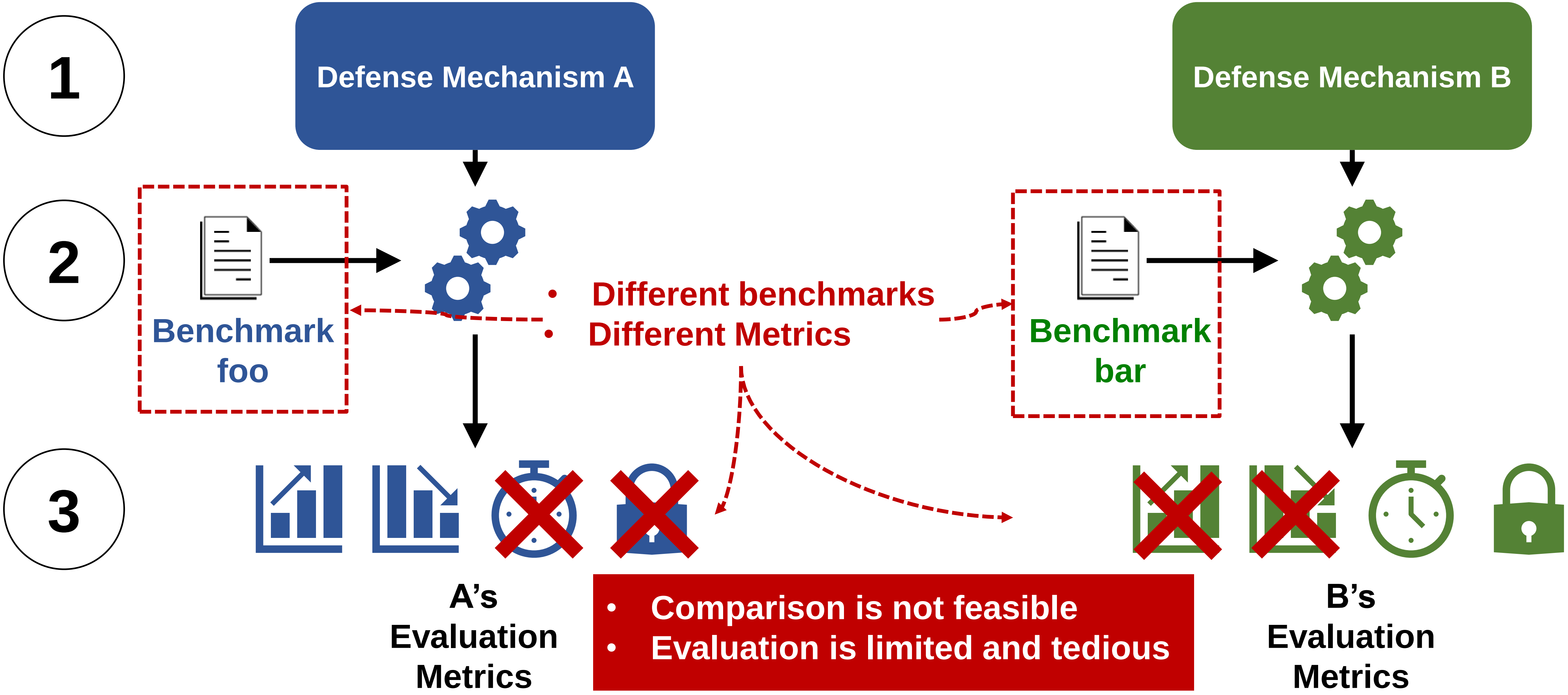
Defense	**Evaluation Type**	
	Benchmark	**Case Study**
TyTan		✓
TrustLite		✓
C-FLAT		✓
nesCheck		✓
SCFP	Dhrystone[1]	✓
LiteHAX	CoreMark[2]	✓
CFI CaRE	Dhrystone[1]	✓
ACES		✓
Minion		✓
EPOXY	BEEBS[3]	✓

[1] R. P. Weicker, “Dhrystone: a synthetic systems programming benchmark,” Communications of the ACM, vol. 27, no. 10, pp. 1013–1030, 1984
[2] EEMBC, “Coremark - industry-standard benchmarks for embedded systems,” http://www.eembc.org/coremark.
[3] J. Pallister, S. J. Hollis, and J. Bennett, “BEEBS: open benchmarks for energy measurements on embedded platforms,” CoRR, vol. abs/1308.5174, 2013.[Online]. Available: http://arxiv.org/abs/1308.5174

IoT-µCs Evaluation (Ideally)

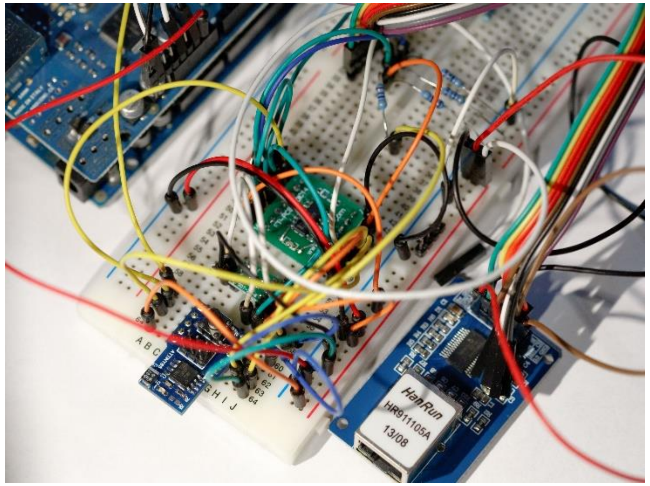


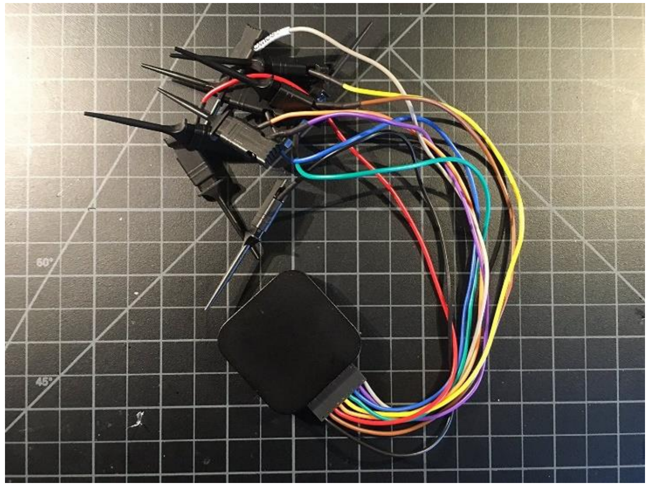
IoT-µCs Evaluation (Reality)

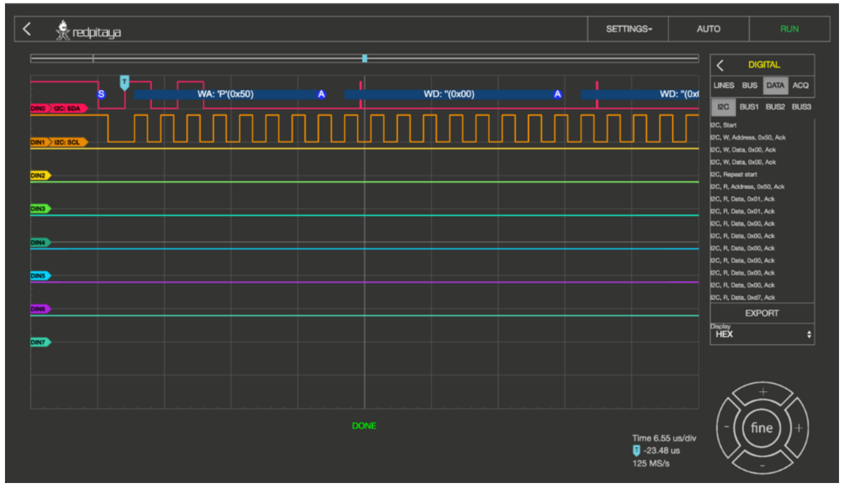


Why not use Existing Benchmark?

- **Current benchmarks are rigid and simplistic.**
  - Many are just one file with simple application.
  - Metrics are limited and cumbersome to collect.
  - Hardware dependent.
- **Do not use peripherals.**
- **No network connectivity.**







Proposed Solution: BenchIoT

- **BenchIoT provides a suite of benchmark applications and an evaluation framework.**

- **A realistic set of *IoT* benchmarks.**
  - Mimics common IoT characteristics, e.g., tight coupling with sensors and actuators.
  - Works for both with/without an OS.

- **Our evaluation framework is versatile and portable.**
  - A software based approach.
  - Can collect metrics related to security and resource usage.

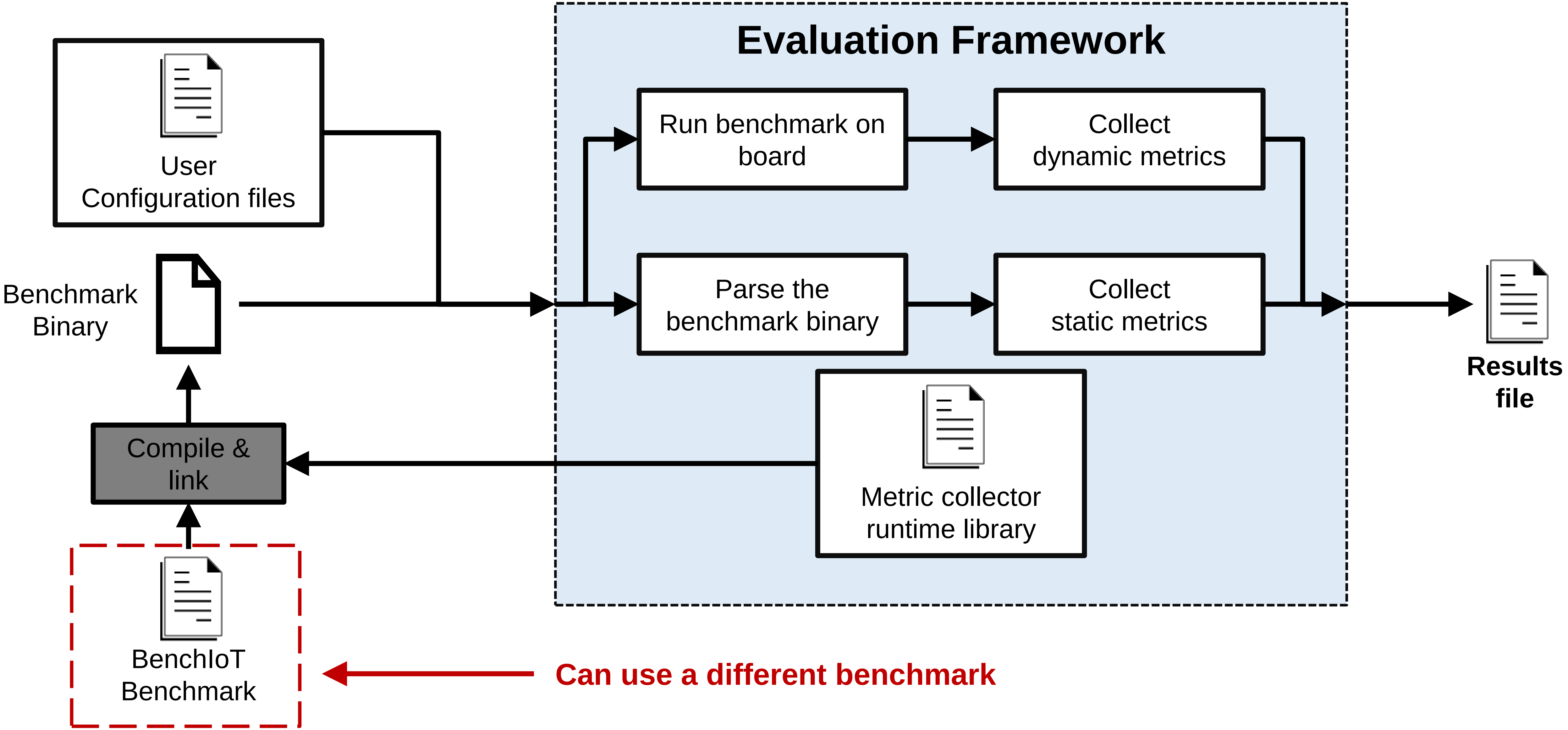
- **Targeted Architecture: ARMv7-M (Cortex-M3,4, and 7 processors).**

Comparison Between BenchIoT and Other Benchmarks

Benchmark	Task Type			Network Connectivity	Peripherals
	Sense	Compute	Actuate		
BEEBS [2]		✓			
Dhrystone [1]		✓			
CoreMark [3]		✓			
IoTMark [4]	✓	✓		Partially (Bluetooth only)	Only I^2C
SecureMark [5]		✓			
BenchIoT	✓	✓	✓	✓	✓

[1] R. P. Weicker, “Dhrystone: a synthetic systems programming benchmark,” Communications of the ACM, vol. 27, no. 10, pp. 1013–1030, 1984
[2] J. Pallister, S. J. Hollis, and J. Bennett, “BEEBS: open benchmarks for energy measurements on embedded platforms,” CoRR, vol. abs/1308.5174, 2013.[Online]. Available: http://arxiv.org/abs/1308.5174
[3] EEMBC, “Coremark - industry-standard benchmarks for embedded systems,” http://www.eembc.org/coremark
[4] EEMBC, “Coremark - industry-standard benchmarks for embedded systems,” http://www.eembc.org/iotmark
[5] EEMBC, “Coremark - industry-standard benchmarks for embedded systems,” http://www.eembc.org/ securemark

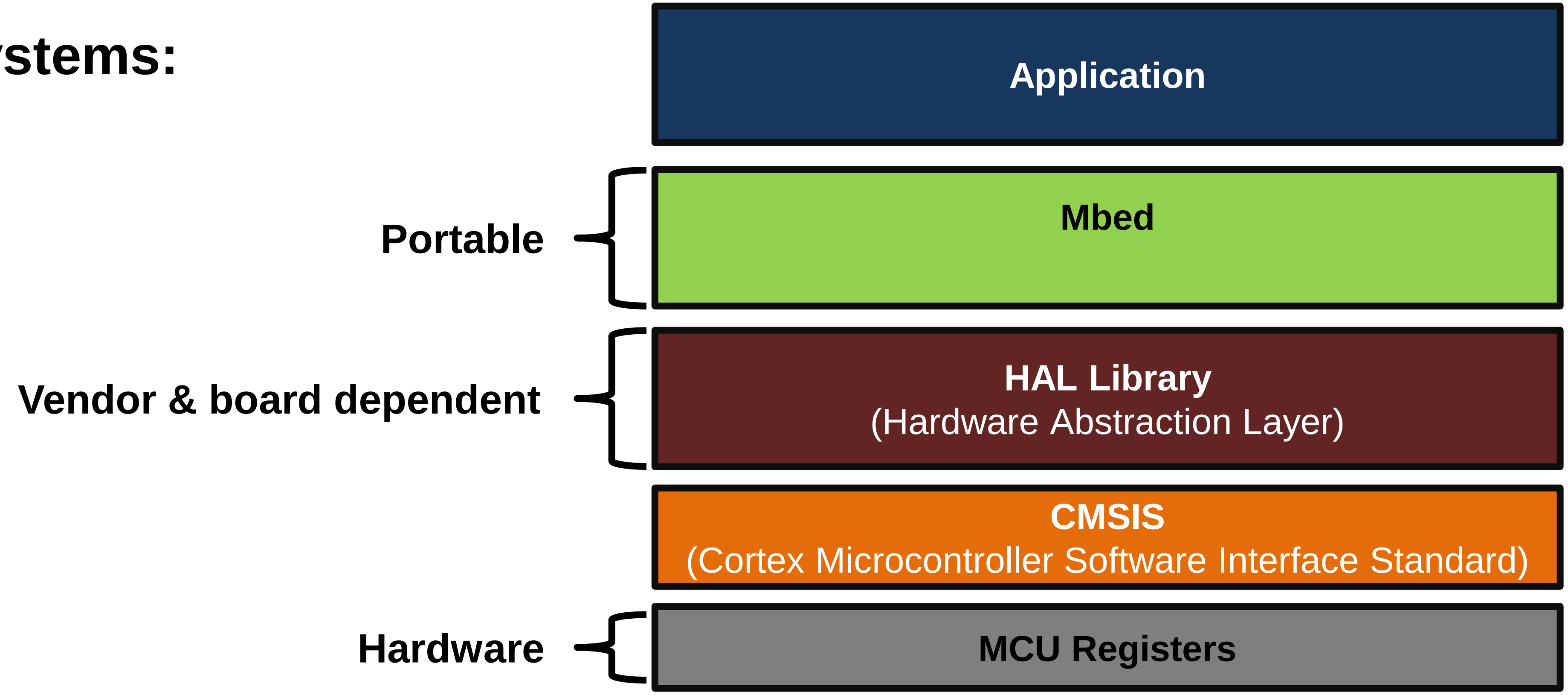
BenchIoT: Overview



BenchIoT Design Feature: (1) Hardware agnostic

- **Applications often depend on the underlying vendor & board.**
  - Memory is mapped differently on each board.
  - Peripherals are different across boards.

- **For Operating systems:**
  - Mbed OS(C++)



BenchIoT Design Feature: (2) Reproducibility

- **Applications are event driven.**
  - Example: User enters a pin.
  - Problem: This is inconsistent (e.g., variable timing).

- **Solution: Trigger interrupt from software.**
  - Creates deterministic timing.
  - Allows controlling the benchmarking execution.

BenchIoT Design Feature: (2) Reproducibility

Normal application

```
/* Pseudocode */
void benchmark(void){
    do_some_computation();
    ...
    ...
    wait_for_user_input();
    read_user_input();
    ...

}
```

This is not deterministic

Deterministic

BenchIoT

```
/* Pseudocode */
void benchmark(void){
    do_some_computation();
    ...
    ...
    trigger_interrupt();
    ...
    read_user_input();
    ...

}
```

BenchIoT Design Feature: (3) Metrics

- **Allows for measurement of 4 classes of metrics: Security, performance, energy, and memory.**

BenchIoT Design Feature: (3) Metrics

: Static metric

: Dynamic metric

Security

- Total privileged cycles
- Privileged Thread cycles
- SVC cycles
- Max Data region ratio
- Max Code region ratio
- DEP
- ROP resiliency
- # of indirect calls

Performance & Energy

- Total execution cycles
- CPU sleep cycles
- Total energy

Memory

- Stack+Heap usage
- Total RAM usage
- Total Flash usage

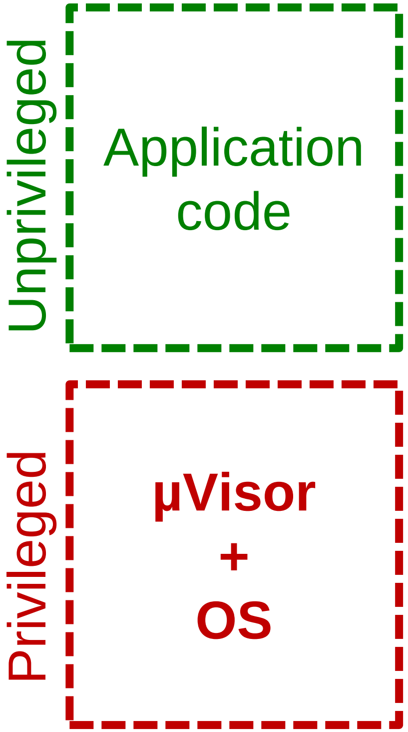
Set of Benchmark Applications

Benchmark	Task Type			Peripheral
	Sense	Compute	Actuate	
Smart Light	✓	✓	✓	Low-power Timer, GPIO, Real-time clock
Smart Thermostat	✓	✓	✓	ADC, Display, GPIO, uSD card
Smart Locker		✓	✓	Serial (UART),Display, uSD Card , Real-time clock
Firmware Updater		✓	✓	Flash in-application programming
Connected Display		✓	✓	Display, uSD Card

- **Boards without non-common peripherals can still run the benchmark.**

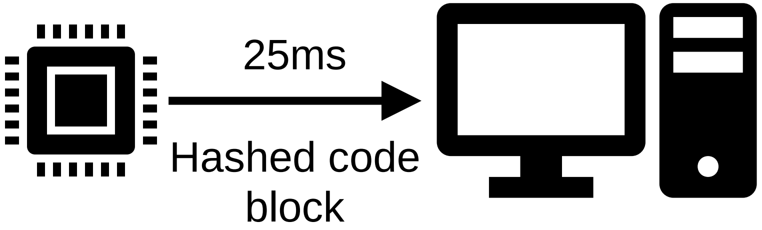
BenchIoT Evaluation: Defense Mechanisms

ARM’s Mbed-µVisor



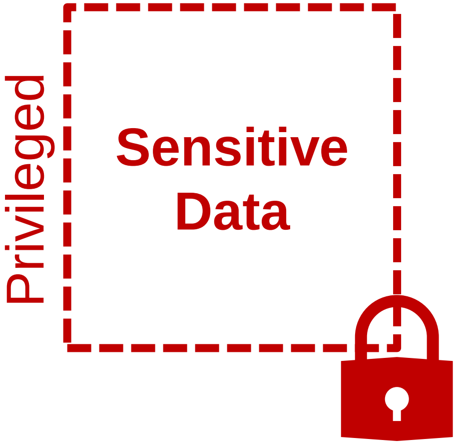
- A hypervisor that enforces the principle of least privilege.

Remote Attestation (RA)



- Verifies the integrity of the code present on the device.
- Uses a real-time task that runs in a separate thread.
- Isolates its code in a secure privileged region.

Data Integrity (DI)

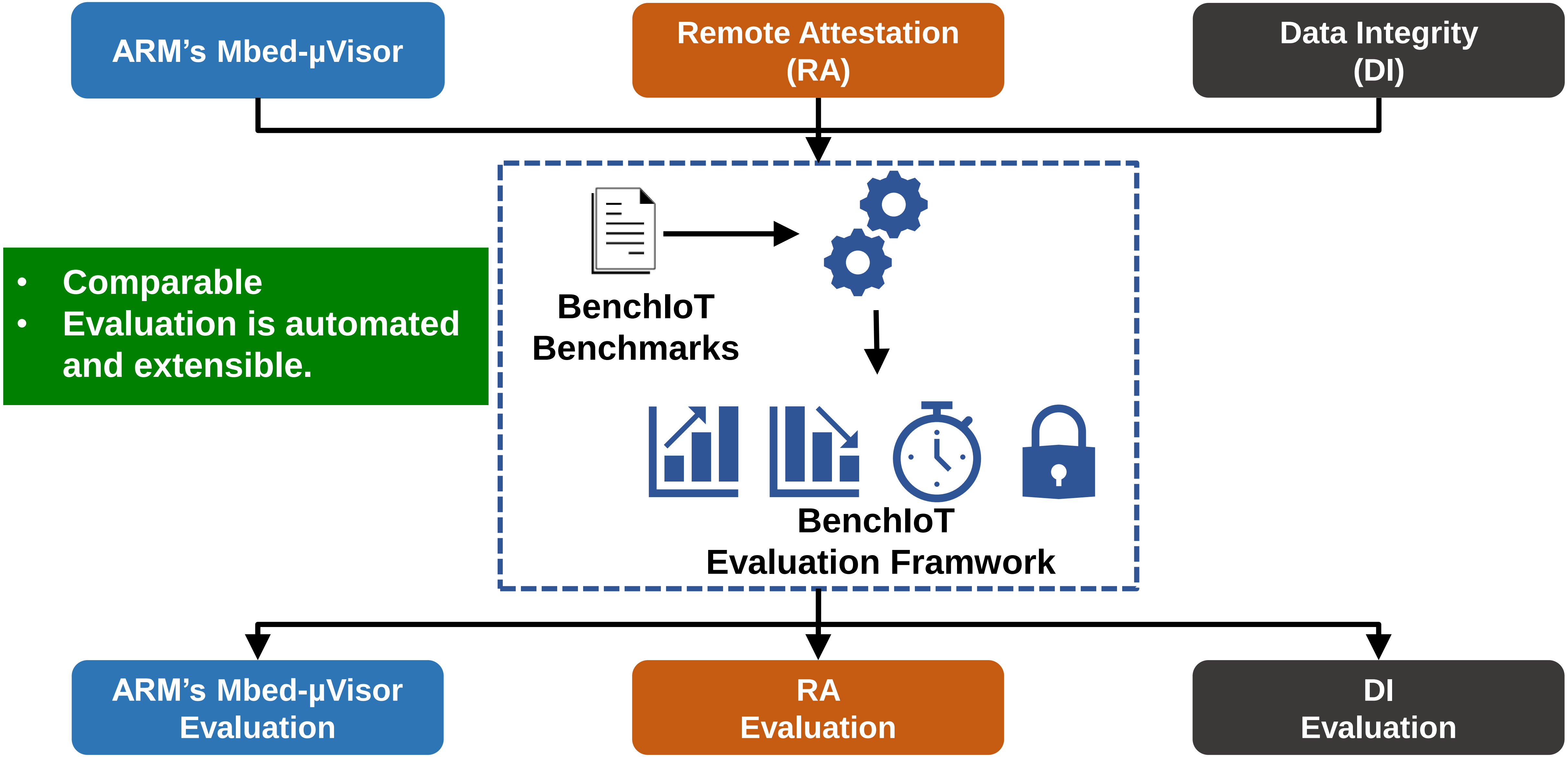


- Isolates sensitive data to a secure privileged region.
- Disables the secure region after the data is accessed.

BenchIoT Evaluation: Defense Mechanisms

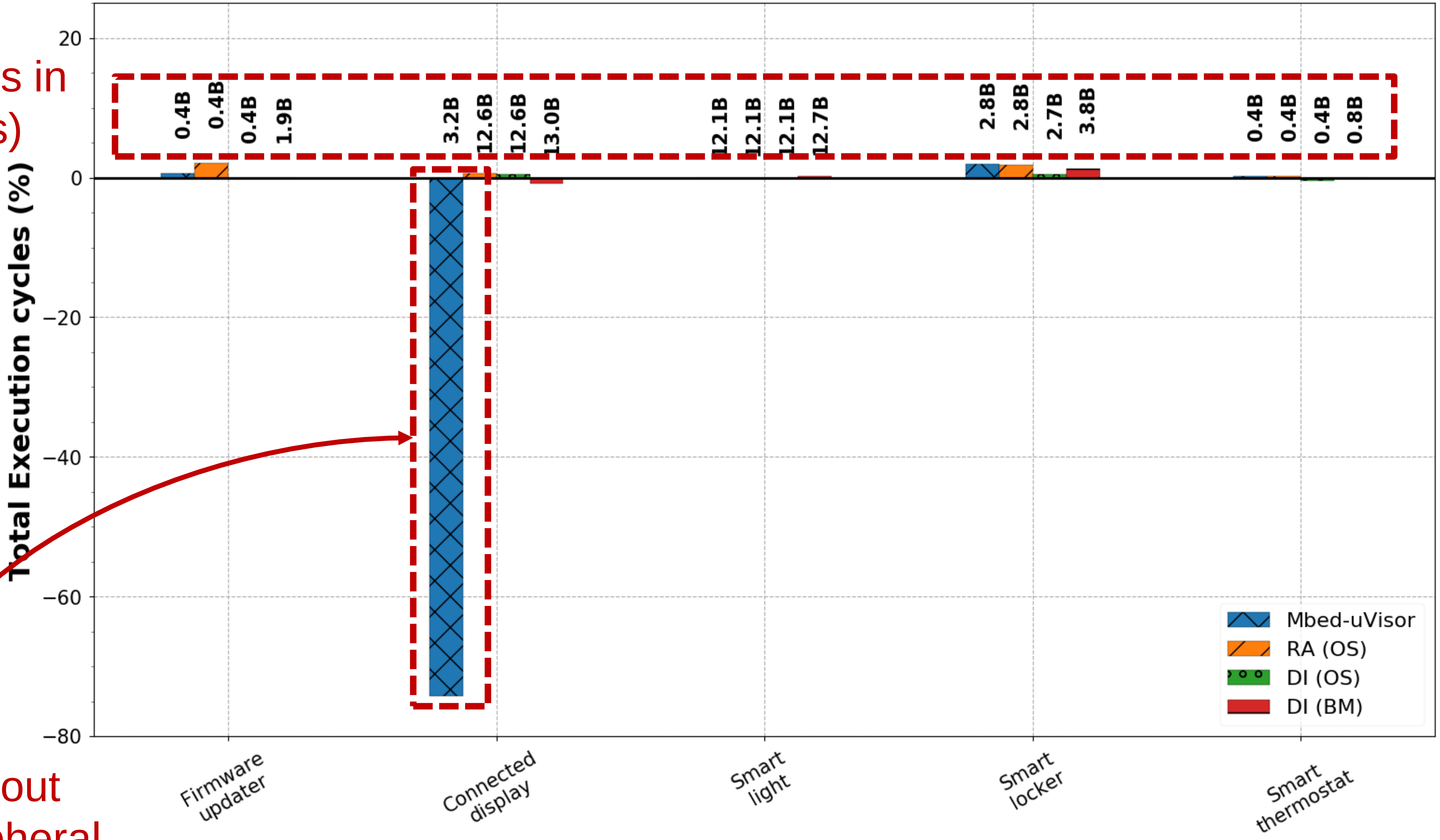
- **The goal is to demonstrate BenchIoT effectiveness in evaluation.**
  - **Non-goal**: To propose a new defense mechanism.
- **ARM's Mbed-µVisor and Remote Attestation (RA) require an OS.**
- **Data Integrity (DI) is applicable to Bare-Metal (BM) and OS benchmarks.**

BenchIoT Evaluation: Defense Mechanisms



Performance Results

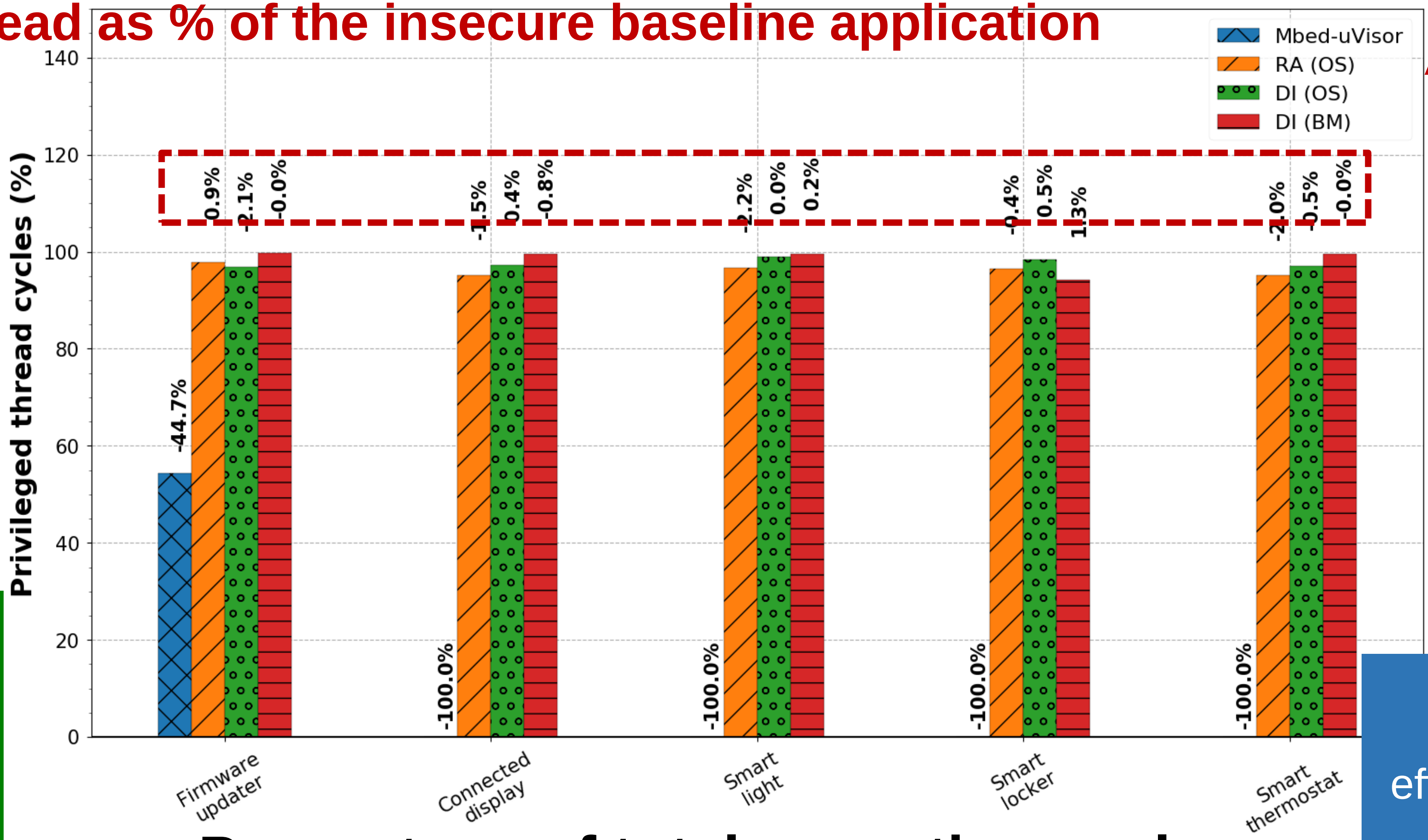
Number of cycles in (Billions/Millions)



Evaluated without the display peripheral

Privileged Execution Minimization Results

- **Overhead as % of the insecure baseline application**



Percentage of total execution cycles

Almost the entire application runs as privileged for all defenses **Except uVisor**

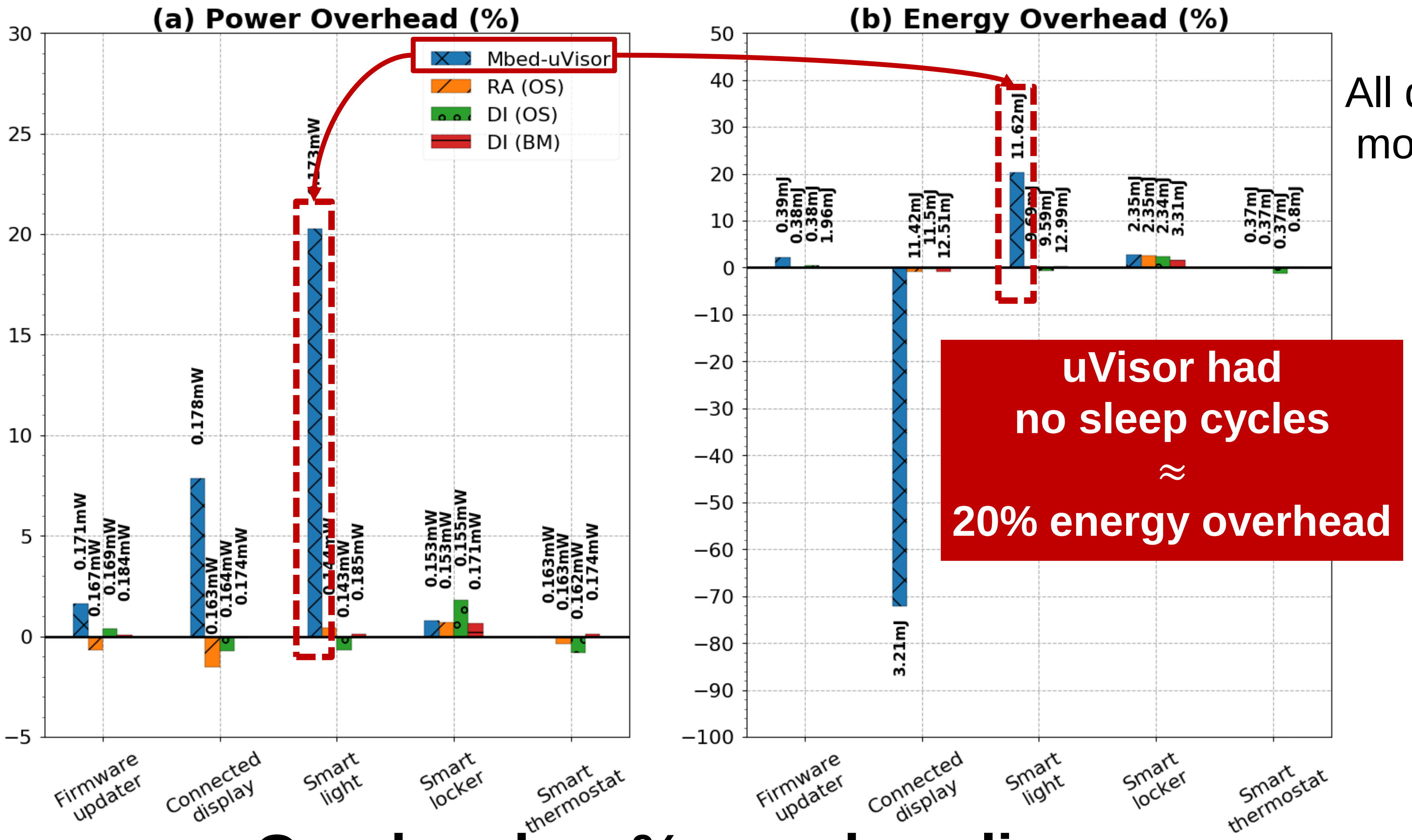
Lower privileged execution → Better Security

uVisor is the most effective defense in reducing privileged execution

Code Injection Evaluation

Defense	Data Execution Prevention (DEP)
Mbed-uVisor	✘ (Heap)
Remote Attestation (OS)	✓
Data Integrity (OS)	✘
Data Integrity (Bare-metal)	✘

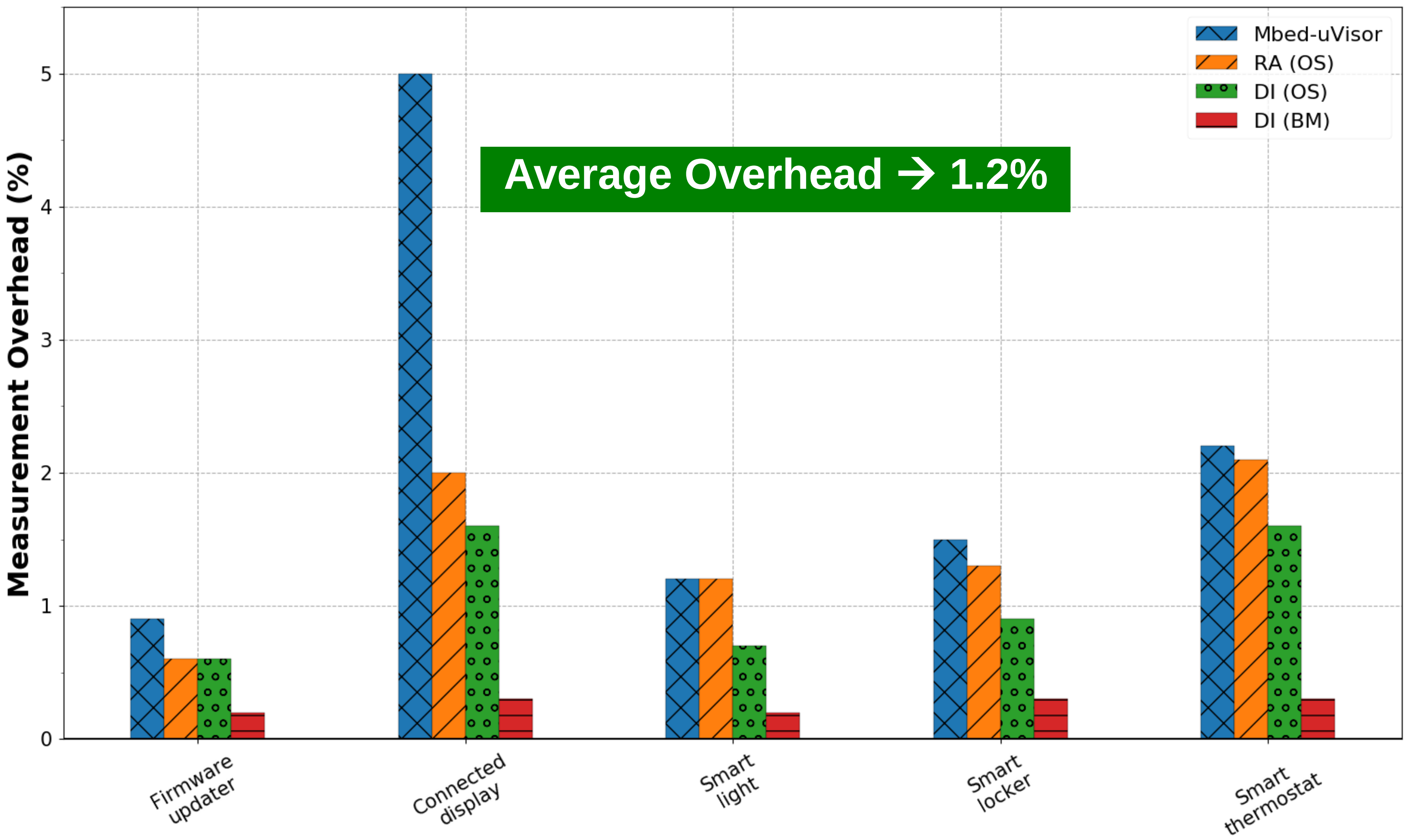
Energy Consumption Results



All defenses had modest runtime overhead

Overhead as % over baseline

Measurement Overhead



Percentage of total execution cycles

BenchIoT: Summary

- **Benchmark suite of five realistic IoT applications.**
  - Demonstrates network connectivity, sense, compute, and actuate characteristics.
  - Applies to systems with/without an OS.
- **Evaluation framework:**
  - Covers security, performance, memory usage, and energy consumption.
  - Automated and extensible.
- **Evaluation insights:**
  - Defenses can have similar runtime overhead, but a large difference in energy consumption.
- **Open source:**
  - https://github.com/embedded-sec/BenchIoT