TNPU: Supporting Trusted Execution with Tree-less Integrity Protection for Neural Processing Unit

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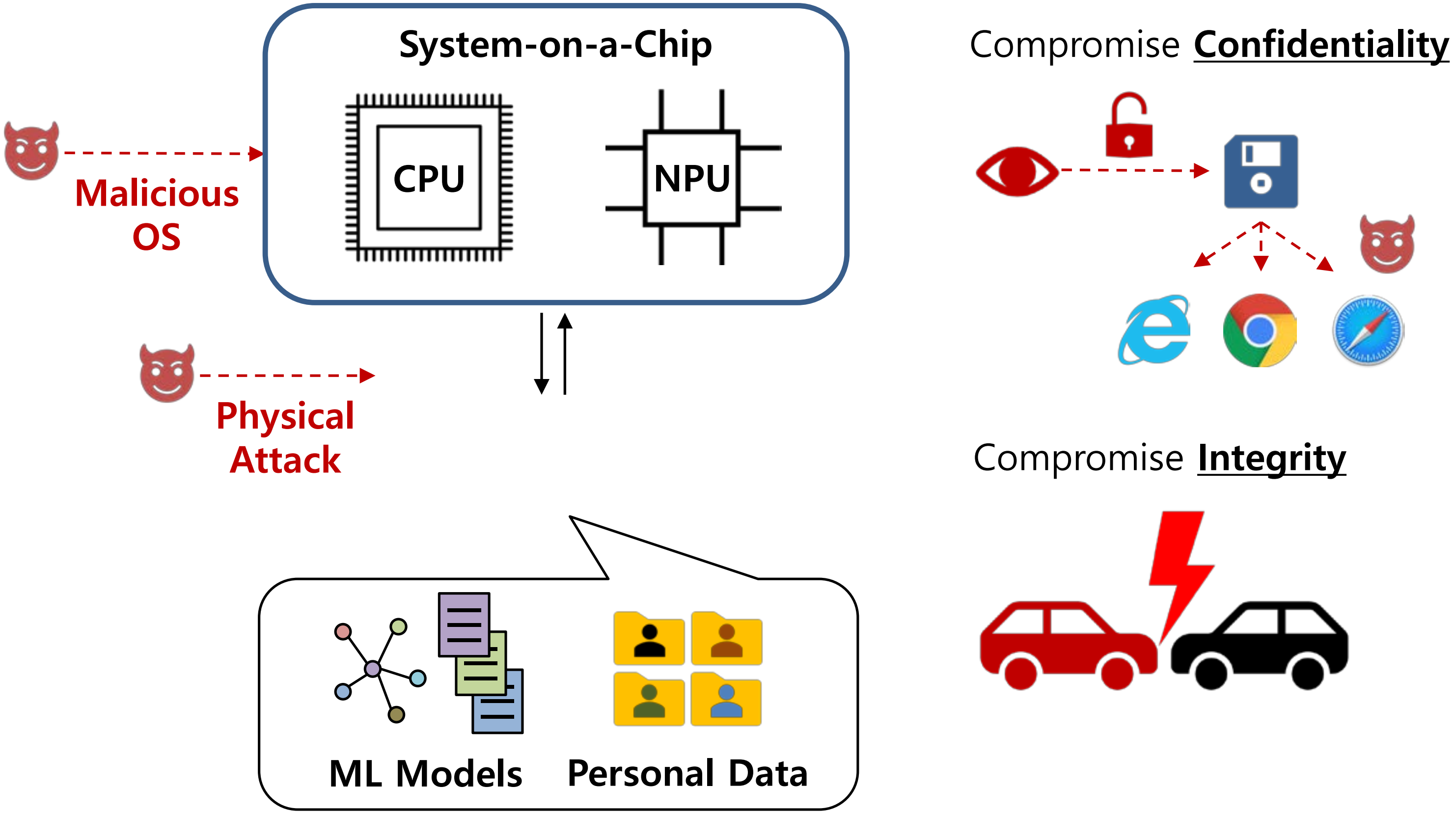
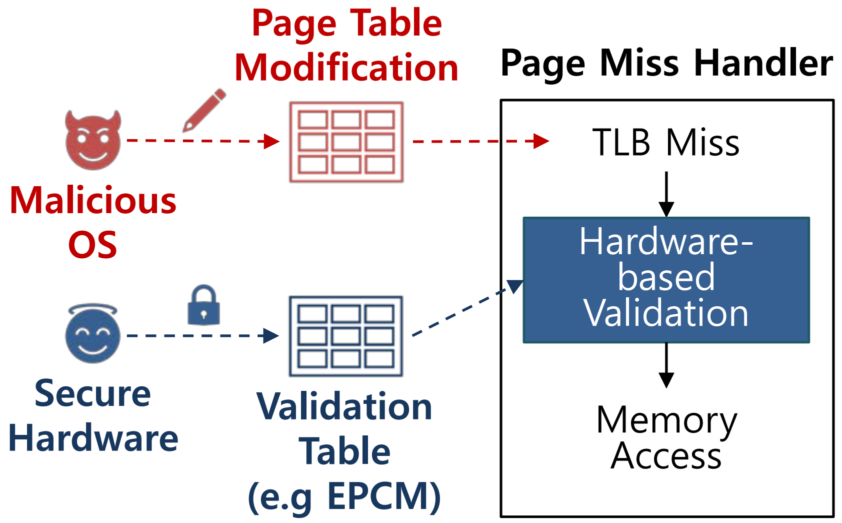
Vulnerabilities of integrated NPU

- NPU is widely used in the form of System-on-a-Chip.



Trusted Execution Environment (CPU)

- Access control
- Counter-based memory protection



Page Table Modification

Page Miss Handler

Malicious OS

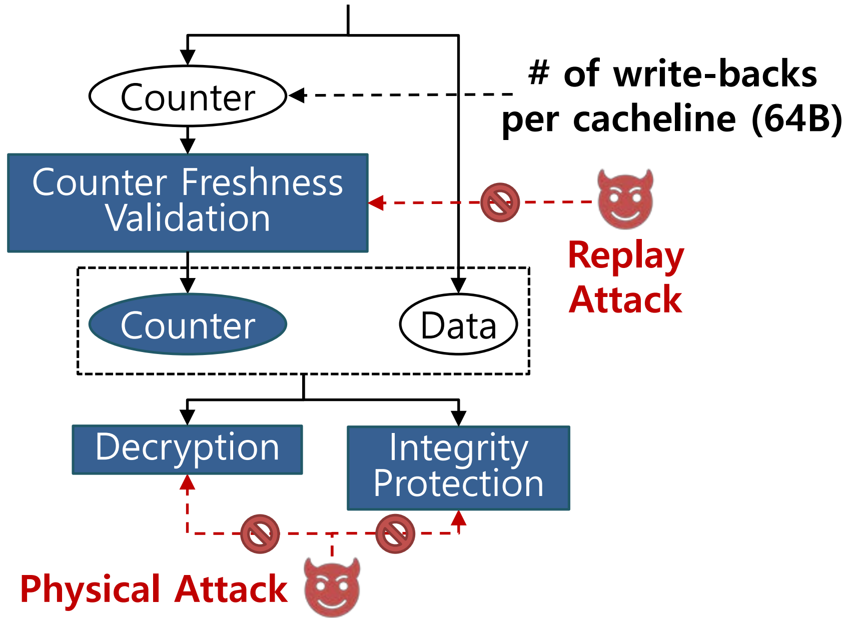
TLB Miss

Hardware-based Validation

Memory Access

Secure Hardware

Validation Table (e.g EPCM)



Counter

# of write-backs per cacheline (64B)

Counter Freshness Validation

Replay Attack

Counter

Data

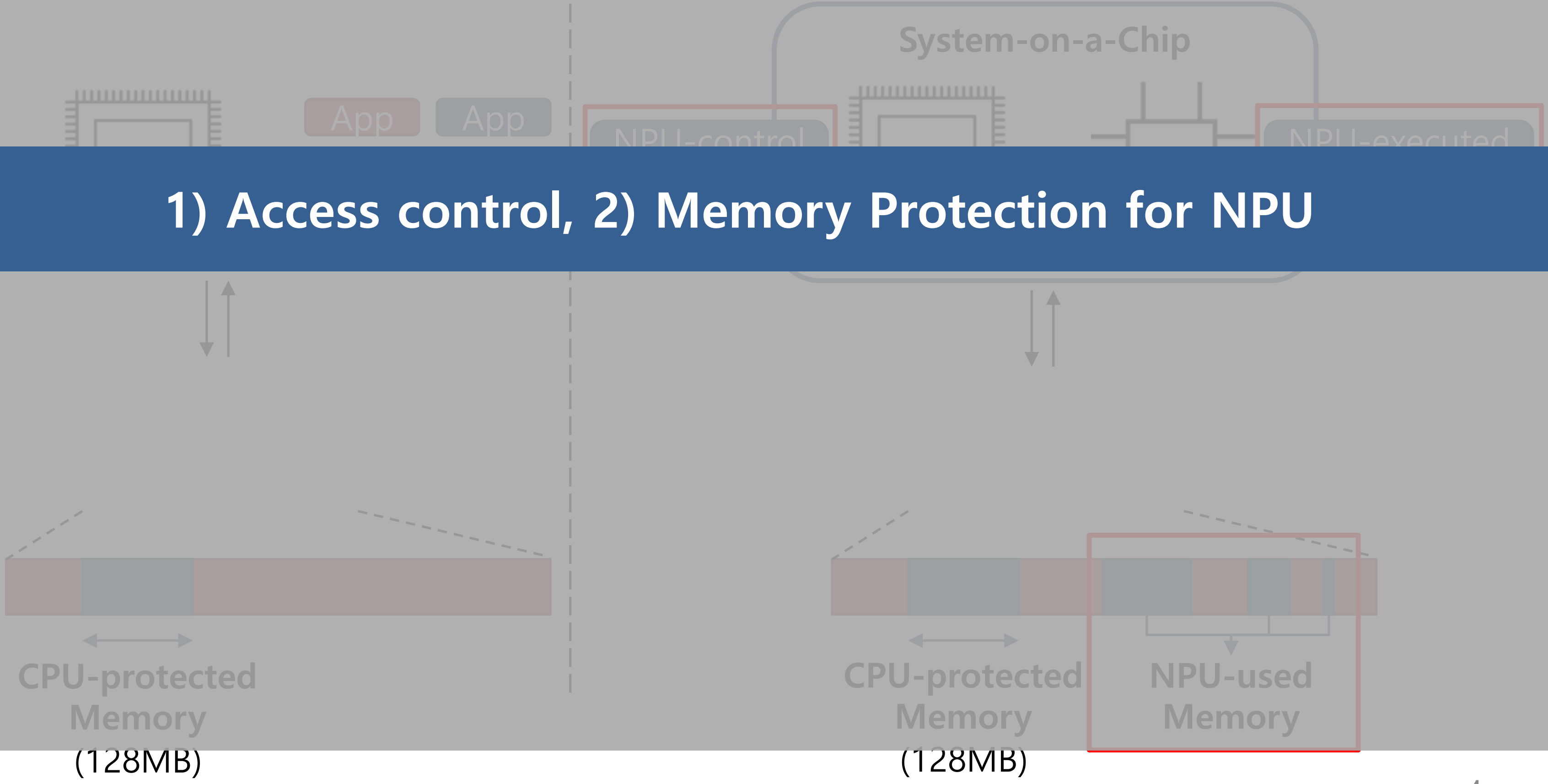
Decryption

Integrity Protection

Physical Attack

Trusted Execution Environment (NPU)

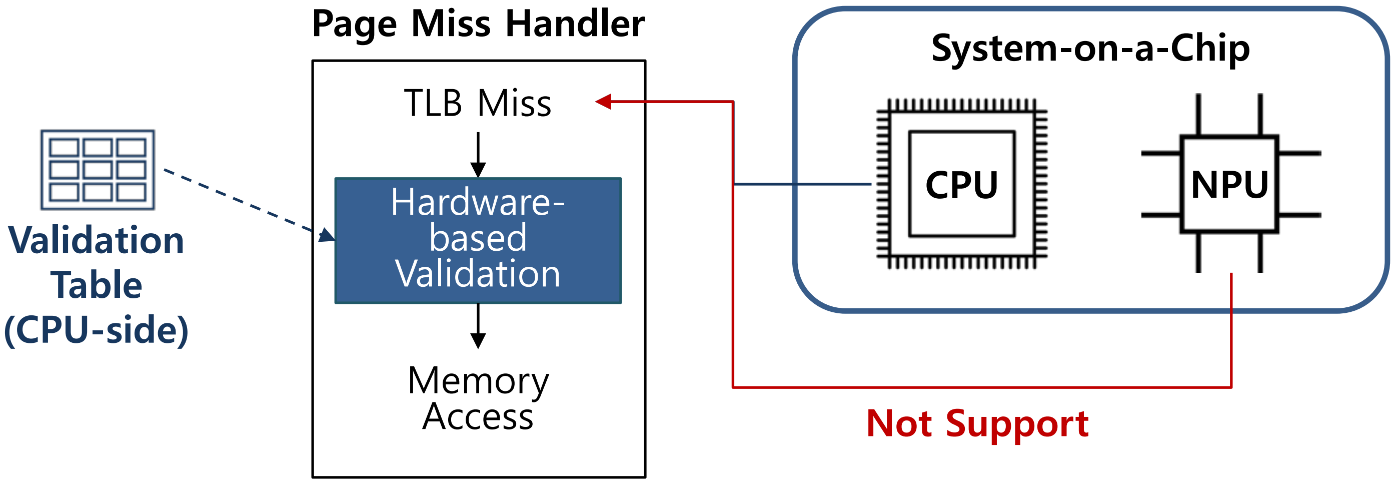
- CPU: On-chip hardware and related software
- TNPU: + NPU-related hardware/software



1) Access control, 2) Memory Protection for NPU

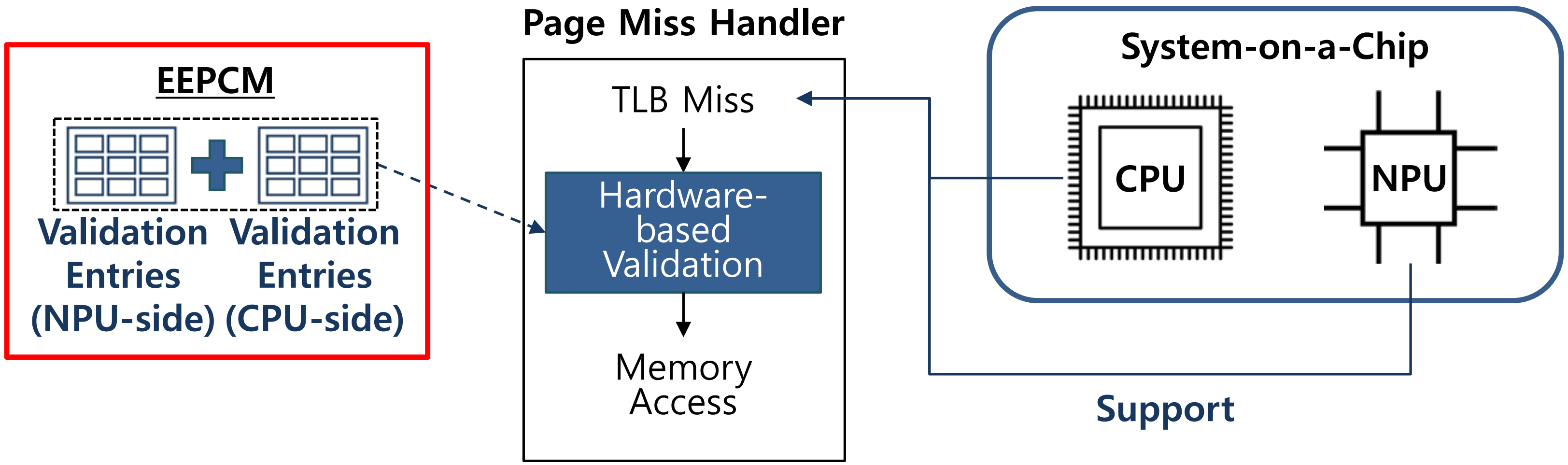
Validate Access from NPU-MMU

- Access control
  - CPU MMU: Traditional validation table
  - NPU IOMMU



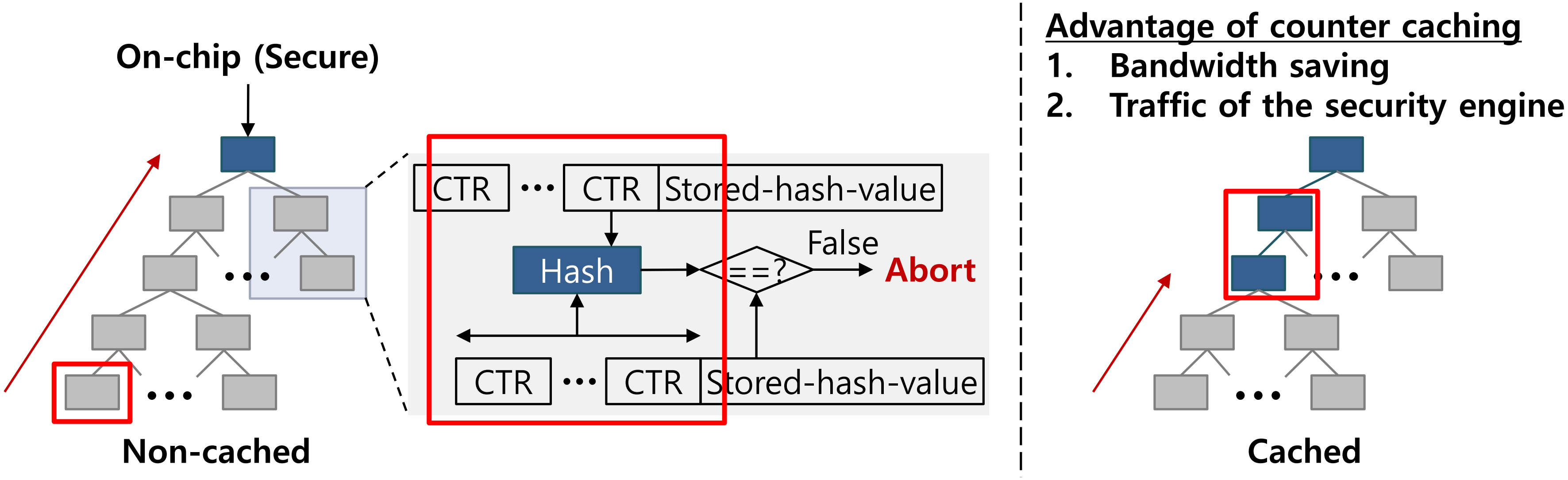
Validate Access from NPU

- Access control: **Extended validation table (EEPCM)**
  - CPU MMU: Traditional validation entries
  - NPU IOMMU: **Additional validation entries**


EEPCM
Validation Entries (NPU-side)
Validation Entries (CPU-side)
Page Miss Handler
TLB Miss
Hardware-based Validation
Memory Access
System-on-a-Chip
CPU
NPU
Support

Naive Memory Protection to NPU

- Memory protection
  - Counter-based encryption & integrity protection
  - **Counter Freshness Validation**

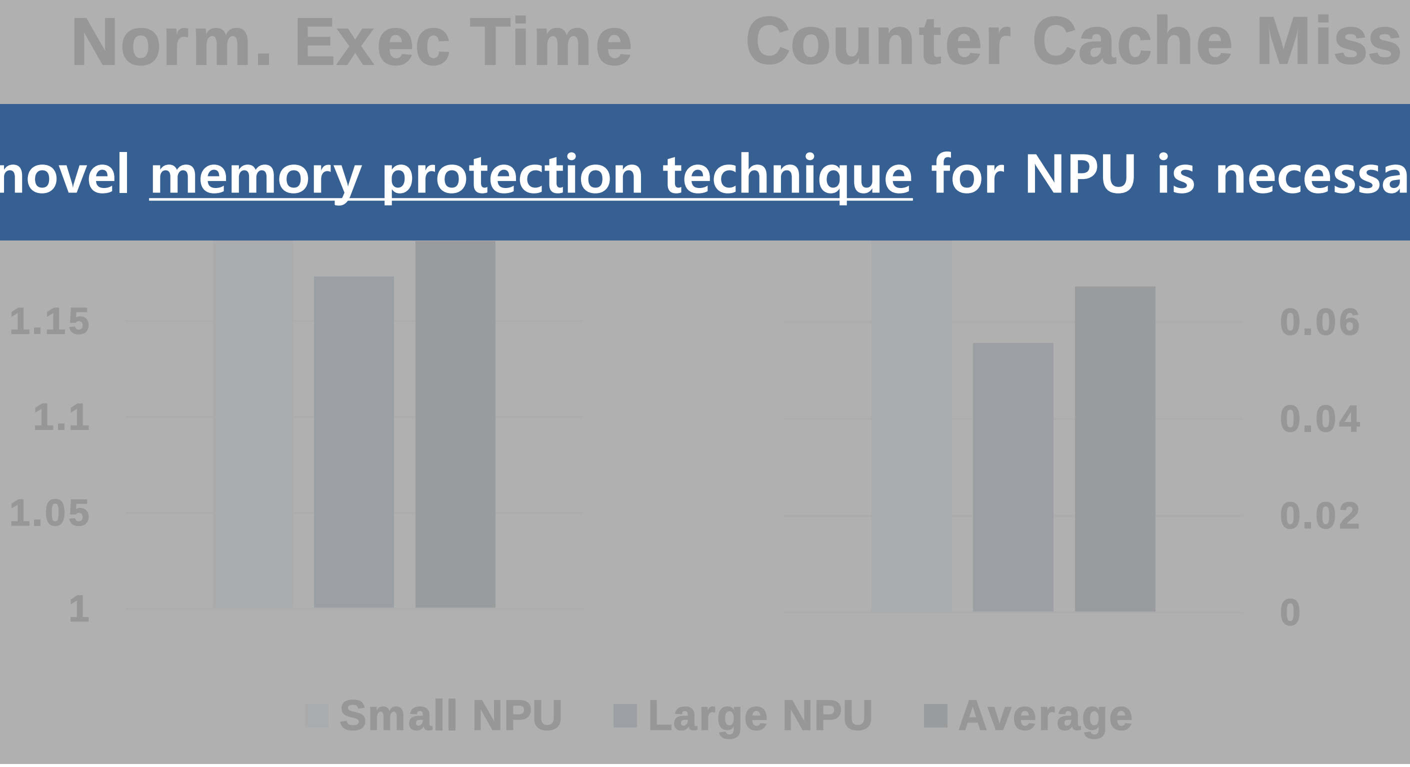


Advantage of counter caching

1. **Bandwidth saving**
2. **Traffic of the security engine**

Naive Memory Protection to NPU

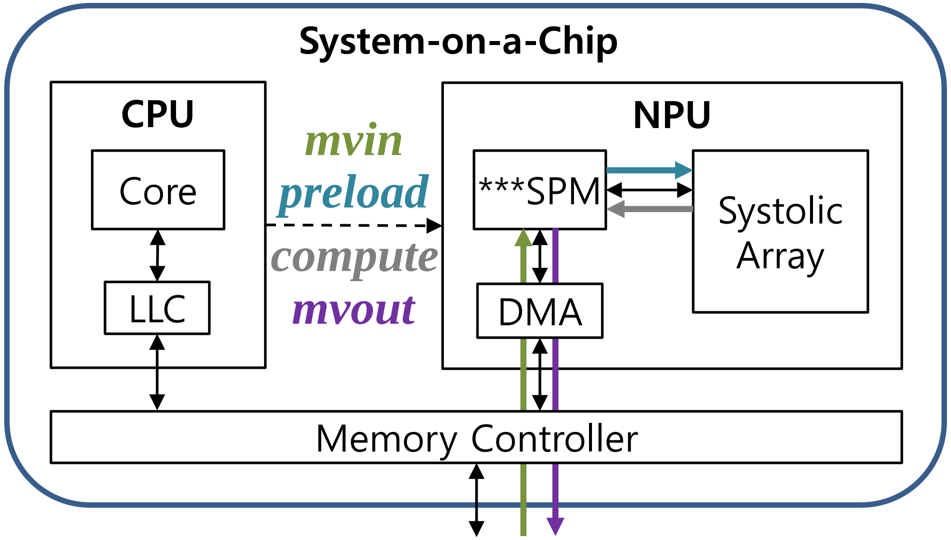
- Average **19.2%** performance degradation
- Reason: Counter-cache miss rate (**7.9%**)

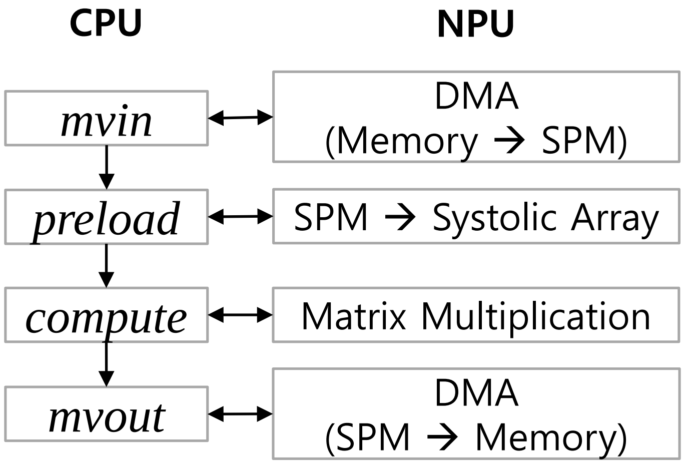


A novel memory protection technique for NPU is necessary!

NPU Execution Model

- Execution: **mvin* → *preload* → *compute* → ***mvout*
  - The **software** controls NPU data movement by commands

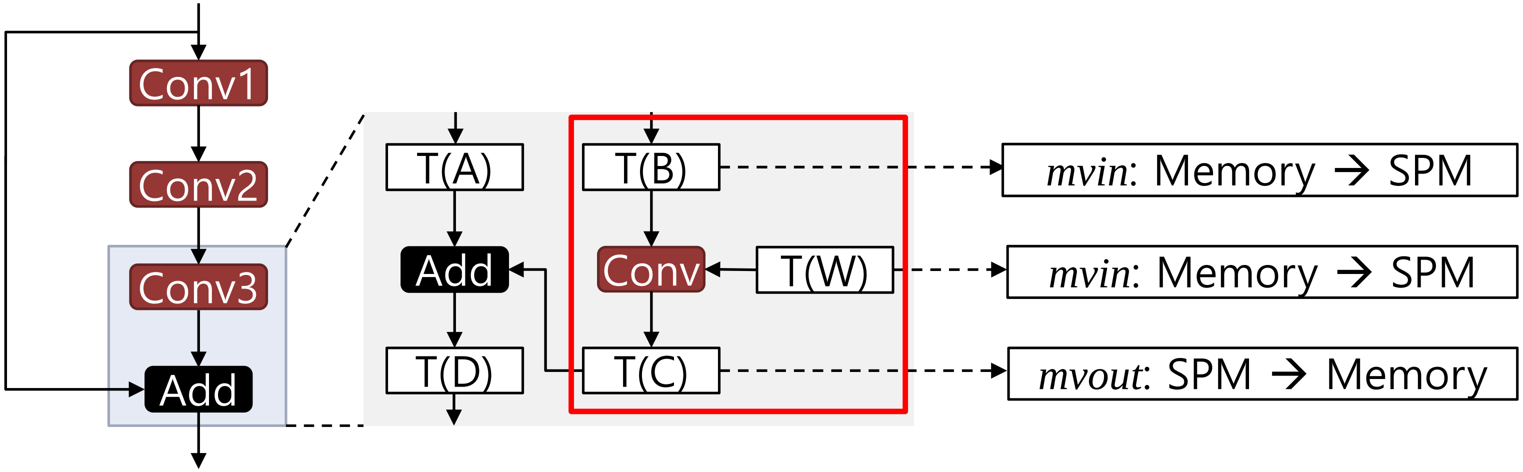




**mvin: move-in, **mvout: move-out, ***SPM: Scratchpad Memory*

Tensor-based Computing

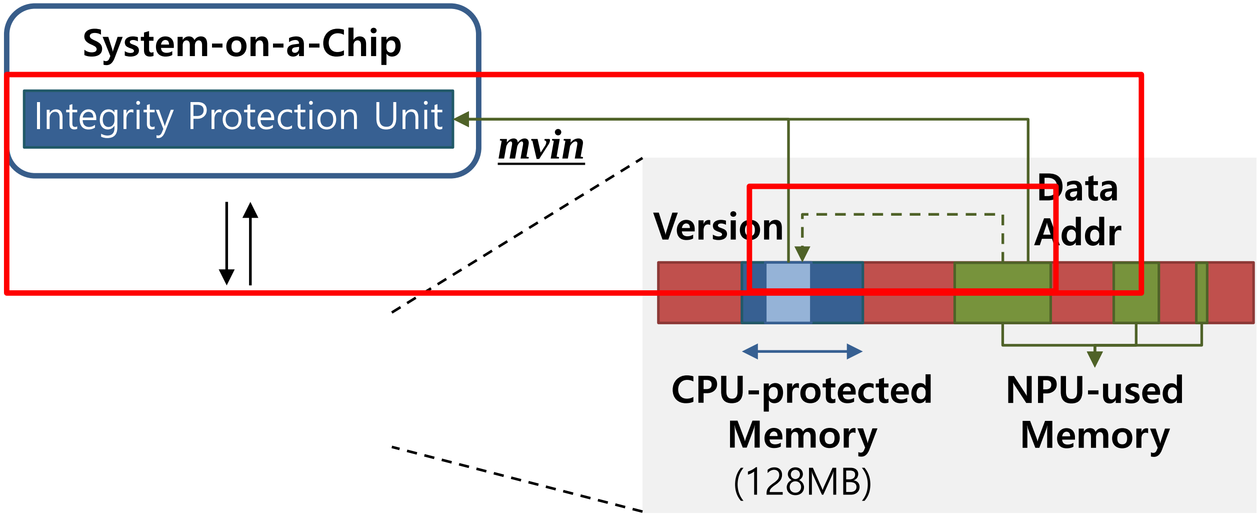
- Tensor-granular computation
  - **Per-tensor version number** is sufficient: Tensor-unit memory access



Residual Block (Resnet 50)

Tree-less Integrity Protection

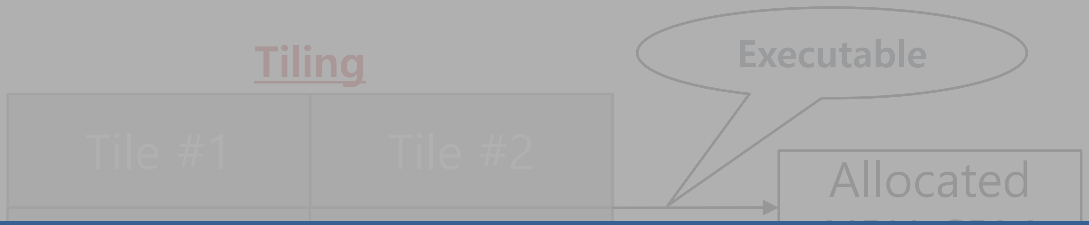
- Counter → **Version number** controlled by **software**
  - Security granularity: Cacheline → **Tensor**
  - Storage requirement: Only **0.14KB** on average



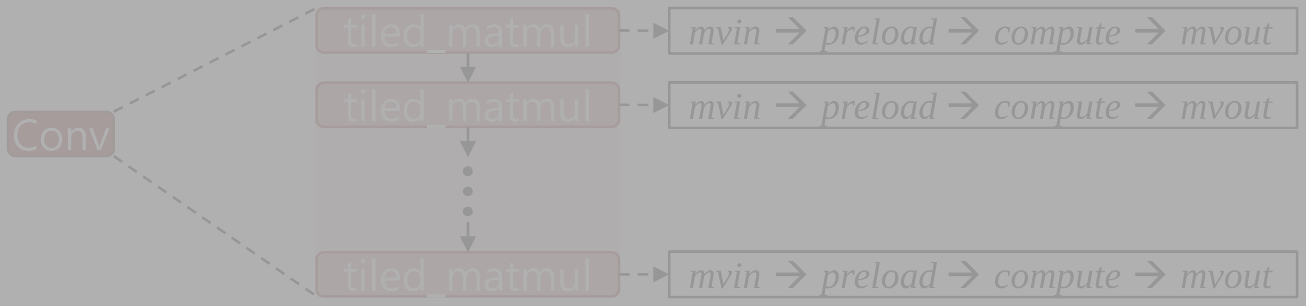
Problem: NPU executes layer operation at once?
(i.e Many large tensors are not fitted into SPM)

Challenge: Intra-layer Computing

- Tensor → One or multiple tiles for intra-layer computing

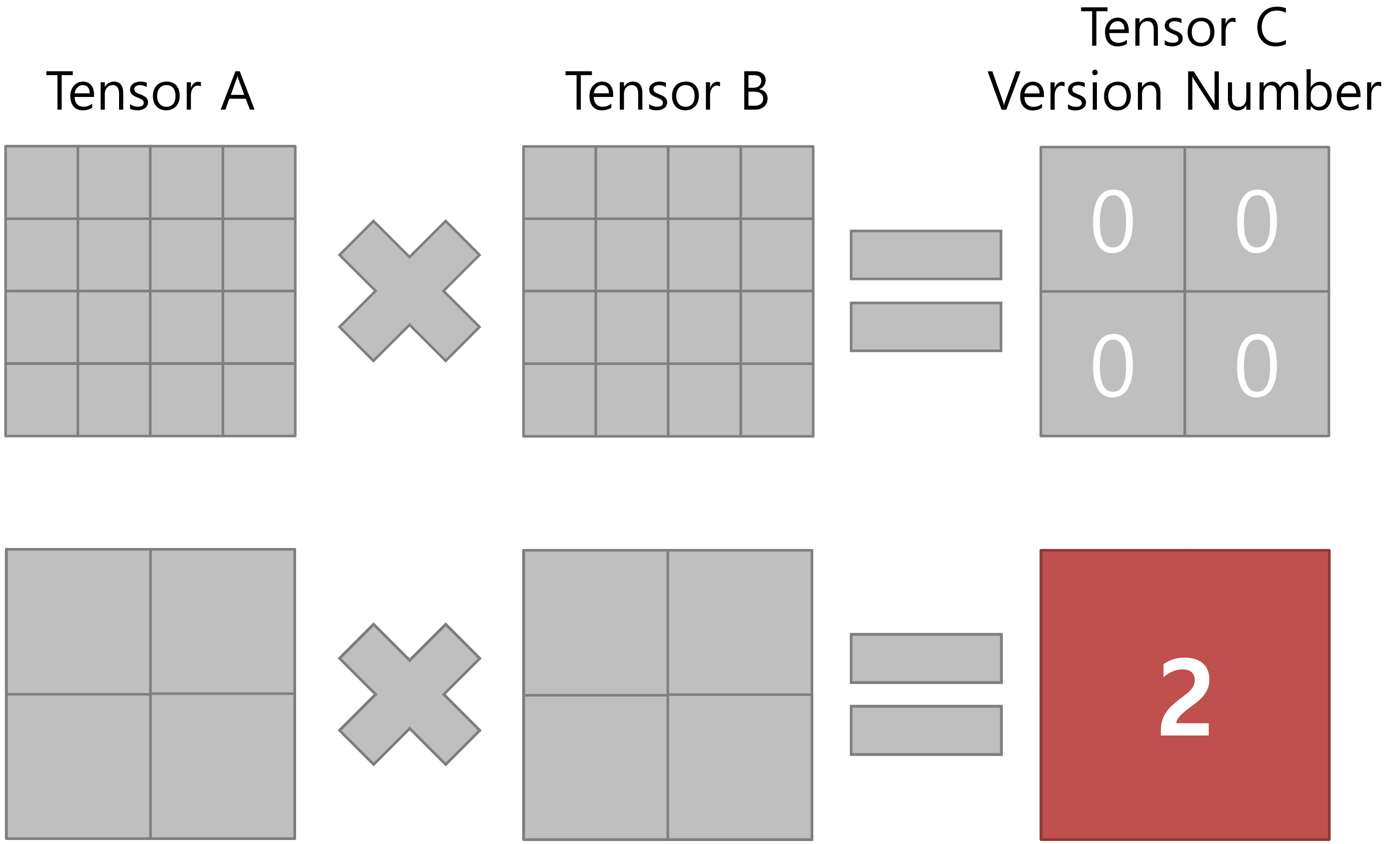


Tile-granular version number is necessary in intra-layer!


Conv
tiled_matmul
tiled_matmul
tiled_matmul
mvin → preload → compute → mvout
mvin → preload → compute → mvout
mvin → preload → compute → mvout

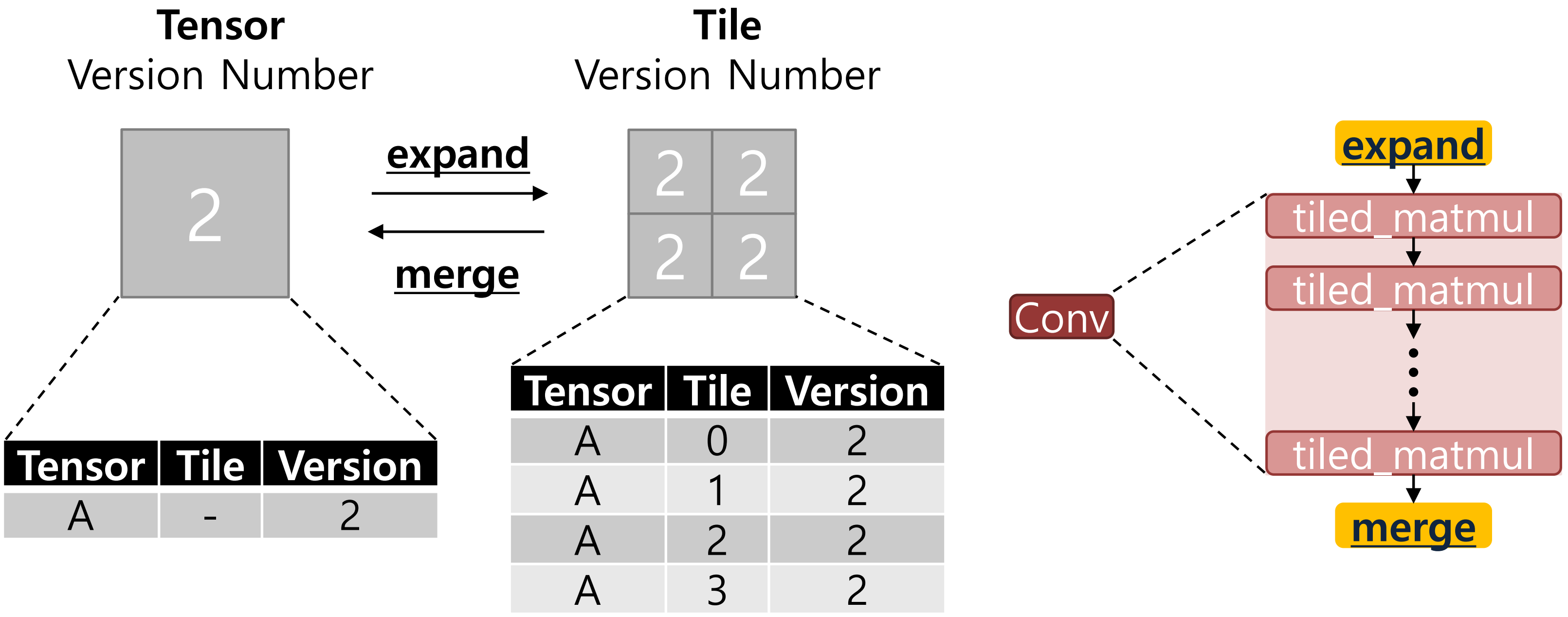
Tile-granular Version Number

- Tensor → One or multiple tiles for intra-layer computing



Tensor/Tile Version Number

- Tensor/Tile version number
  - Granularity: Cacheline → Tensor/**Tile (Intra-layer)**
  - Storage requirement: Only **1.3KB** on average
- **expand**, **merge**: Granularity translation operation



Tensor	Tile	Version
A	-	2

Tensor	Tile	Version
A	0	2
A	1	2
A	2	2
A	3	2

Evaluation Environment

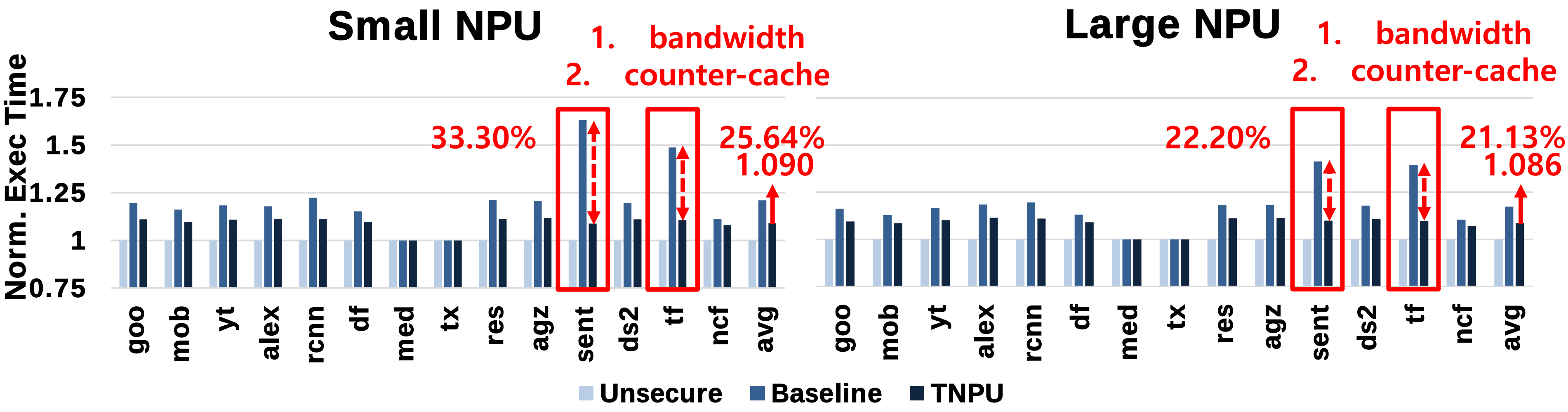
- Cycle-level simulation modified from *SCALE-Sim
- Two edge-level system-on-a-chip configurations
  - Samsung Exynos 990 (Small NPU), ARM Ethos N77 (Large NPU)
- Workloads: 14 models in MLPerf, DeepBench

	Small NPU (Samsung Exynos 990)	Large NPU (ARM Ethos N77)
PE	32 x 32	45 x 45
Bandwidth	11 GB/s (4 channels)	22 GB/s (4 channels)
Frequency	2.75 GHz (both processor/memory)	1 GHz (both processor/memory)
SPM	480KB in total	1MB in total
Precision	Float16	Float16

* A systematic methodology for characterizing scalability of DNN accelerators using SCALE-Sim (ISPASS 2020)

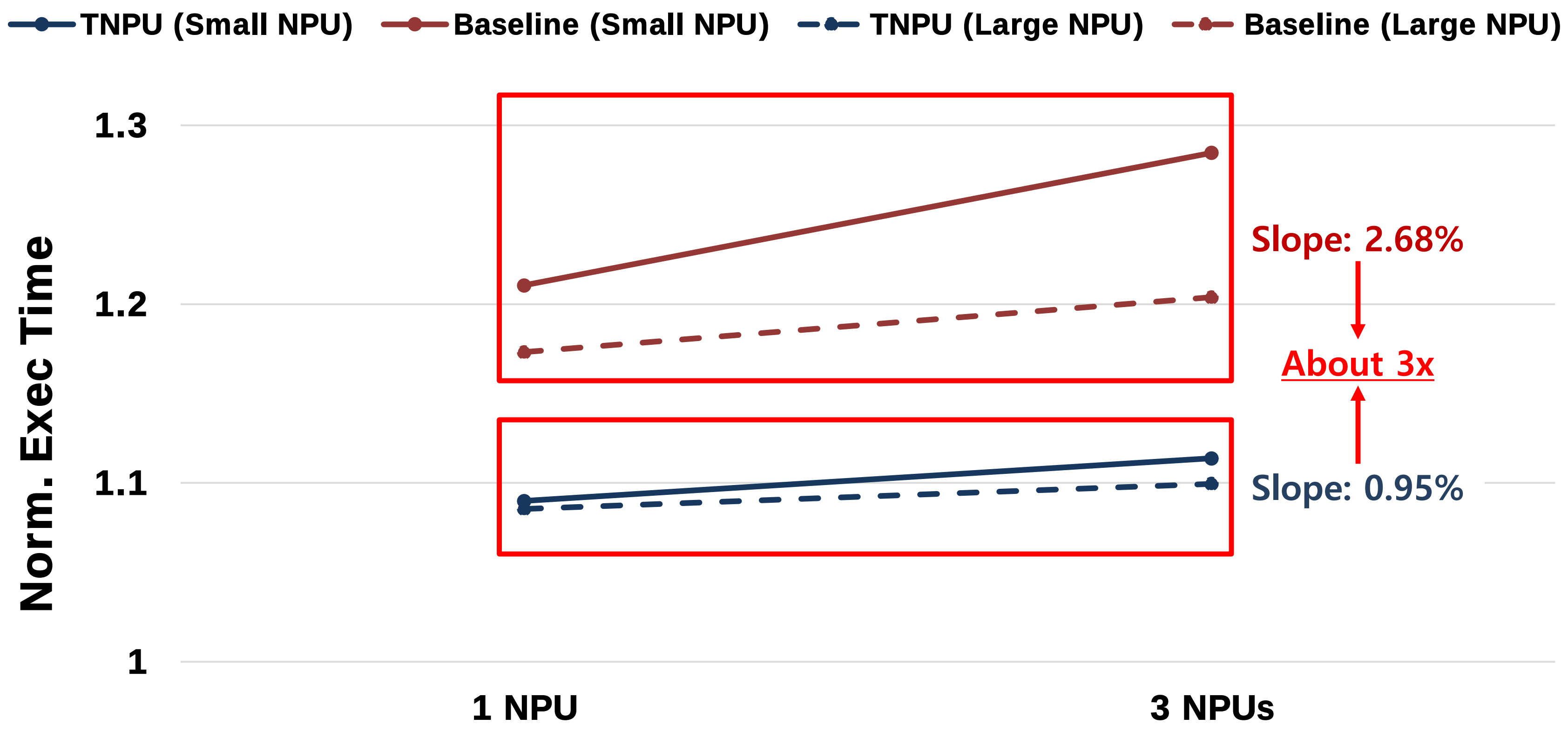
Evaluation Result (Single NPU)

- Performance improvement: **8.75%**
  - Data traffic reduction: **7.67%**
- Remaining performance degradation: **8.80%** (Comp. Unsecure)
  - Stored-hash-value (Message-authentication-code; MAC)



Evaluation Result (Multiple NPUs)

- Scalability: Slope (TNPU) < Slope (Baseline)
- Performance improvement: 8.75% → **11%**



Summary

- **Result**
  - Trusted Execution environment for NPU
  - Performance improvement: **8.75%** (single), **11%** (3-NPU)
- **Challenge**
  - Counter tree overhead
- **Idea**
  - Counter → Tensor/tile-granular version number
- **Further Work**
  - Stored-hash-value (MAC) optimization

Thank you