

Low-Power Neural Network Accelerators: Advancements in Custom Floating-Point Techniques

Yarib Nevarez

Universität Bremen

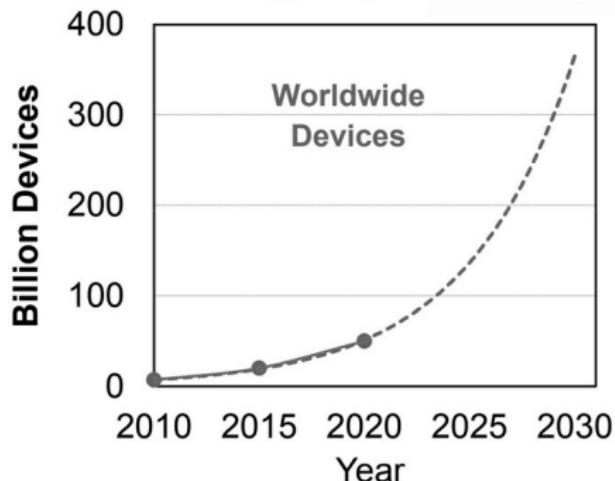
May 22, 2024

Introduction

Expansion of IoT and TinyML: Requirements, Accelerators, and Challenges

Internet-of-Things (IoT) in Smart Cities and Industry 4.0

Any device Anybody Anywhere Any business Any network Anytime

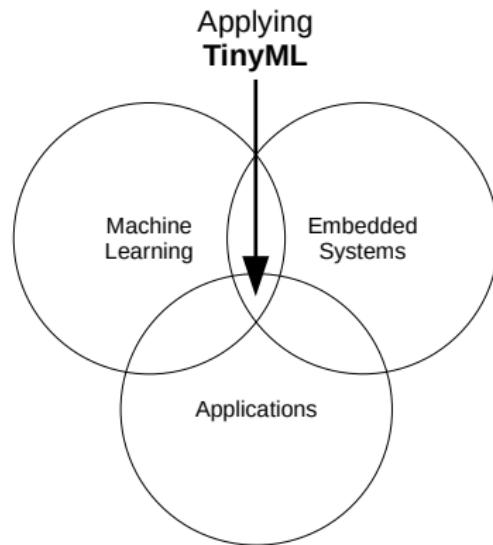


Loh, Kou-Hung Lawrence. "1.2 Fertilizing AIoT from roots to leaves." In 2020 IEEE International Solid-State Circuits Conference-(ISSCC), pp. 15-21. IEEE, 2020.

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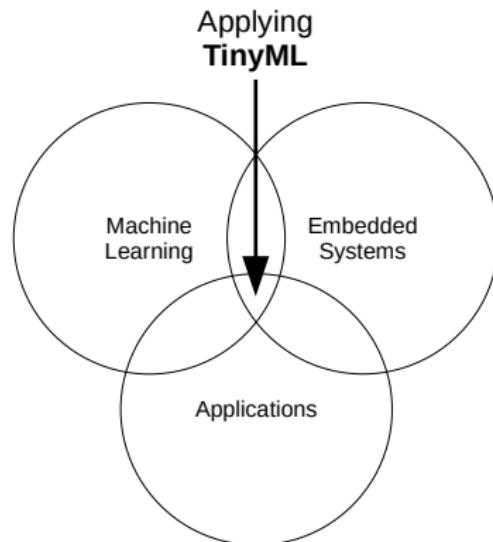
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Neural network accelerators



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Aspects for long-term sustainability:

Energy and resource efficiency

Quality preservation

Application versatility

Platform compatibility

On-device training

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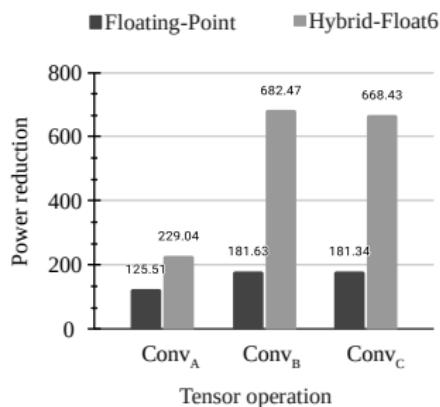
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Power reduction relative to CPU



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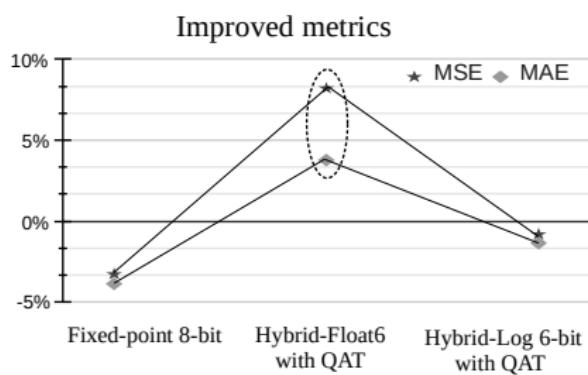
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Model versatility

FC (2), Linear

FC ($E = 64$), ReLu

FC ($D = 196$), ReLu

Flatten

2×2 MaxPool, stride 2

BatchNormalization

3×3 Conv ($C = 60$), ReLu

2×2 MaxPool, stride 2

BatchNormalization

3×3 Conv ($B = 55$), ReLu

2×2 MaxPool, stride 2

BatchNormalization

3×3 Conv ($A = 50$), ReLu

Input tensor ($F \times T \times S$)

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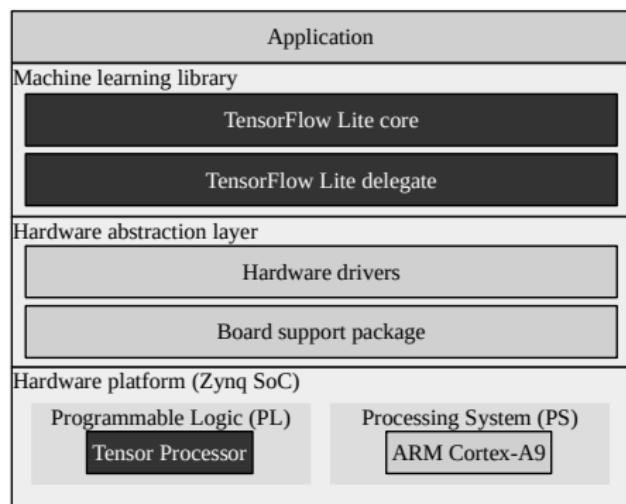
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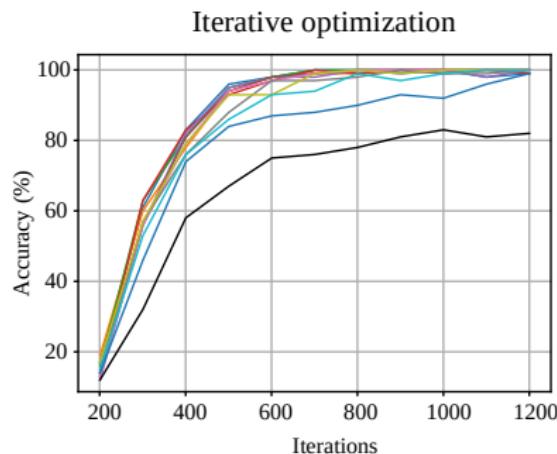
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Aspects for long-term sustainability:

Current state-of-the-art methods:

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Aspects for long-term sustainability:

- Energy and resource efficiency**
- Quality preservation**
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Current state-of-the-art methods:

- Extreme quantization**
Fails to adequately meet fundamental aspects, particularly in **complex problems** and **mission-critical applications**.

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Current state-of-the-art methods:

- Extreme quantization**
Fails to adequately meet fundamental aspects, particularly in **complex problems** and **mission-critical applications**.
- Fixed precision**
Fails to adequately adapt to the ongoing technological shift towards **on-device training**.

Goal and Objectives

- **Goal:** To establish a sustainable, efficient, and universally applicable neural network acceleration technique that supports inference and facilitates on-device training in extreme edge devices, ensuring future-proof and broad applicability. This approach integrates hybrid custom floating-point (FP) computation.

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 - Investigate custom FP computation
 - Conduct performance evaluation

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 - Conduct performance evaluation
 - Analyze impact
 - Ensure cross-platform compatibility

Outline

- 1 Methodology
- 2 Custom Floating-Point MAC Designs and Quantization Techniques
- 3 Case Studies
- 4 Conclusions

1 Methodology

2 Custom Floating-Point MAC Designs and Quantization Techniques

3 Case Studies

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Methodology

Trans-Precision Neural Network Deployment for Low-Power Embedded Systems

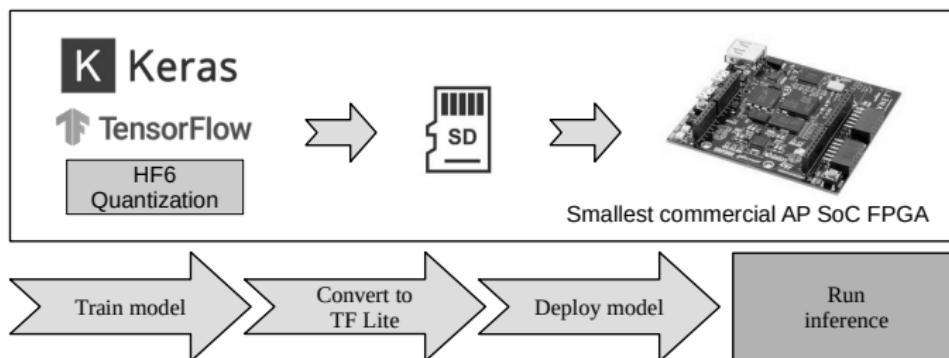
The methodology efficiently deploys and accelerates floating-point neural networks on embedded systems, optimizing performance, energy consumption, and hardware utilization.

Characteristics:

Streamlined hardware architecture

Custom floating-point arithmetic

Neural network execution without quantization processes



Methodology

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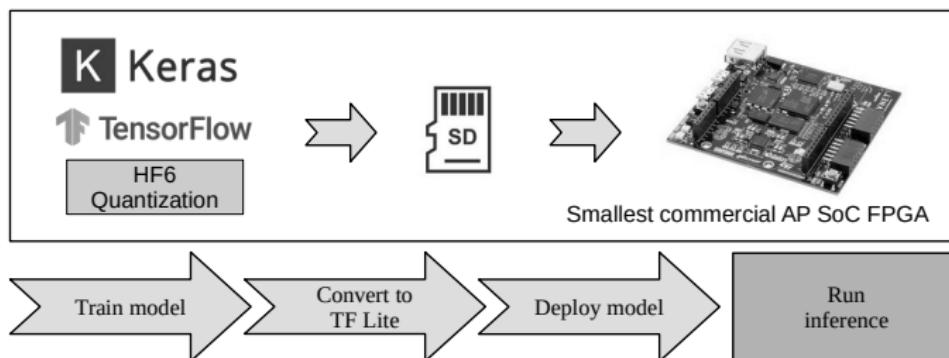
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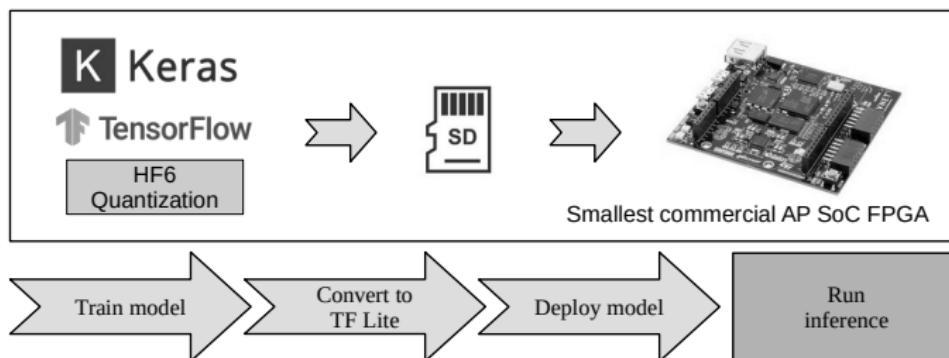
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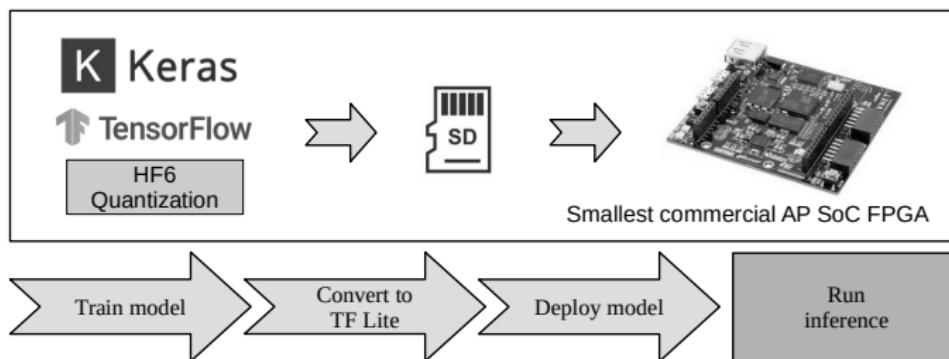
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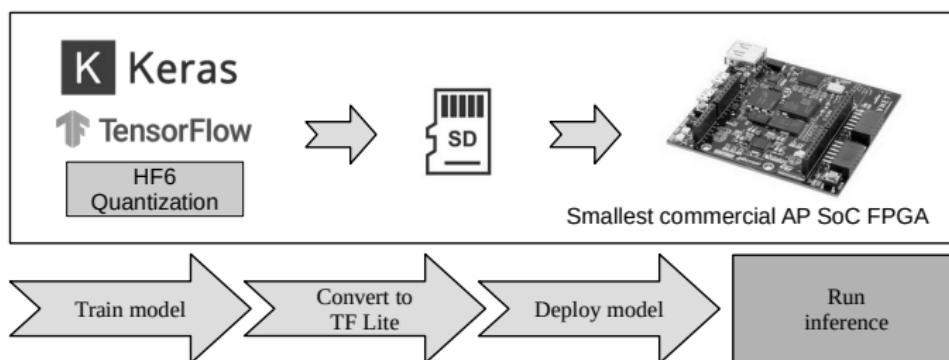
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Abstraction levels:

1. Model deployment
2. System infrastructure
3. Streamlined acceleration
4. Optimized processing

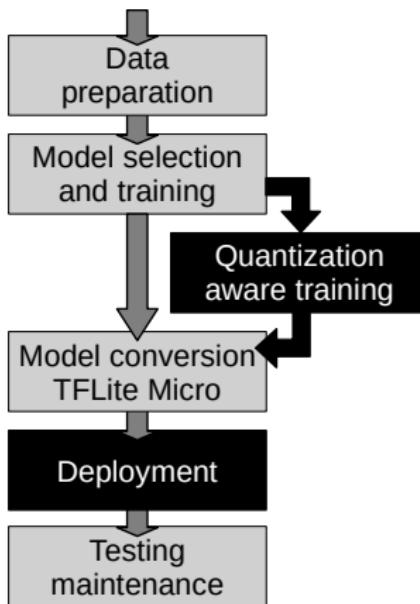
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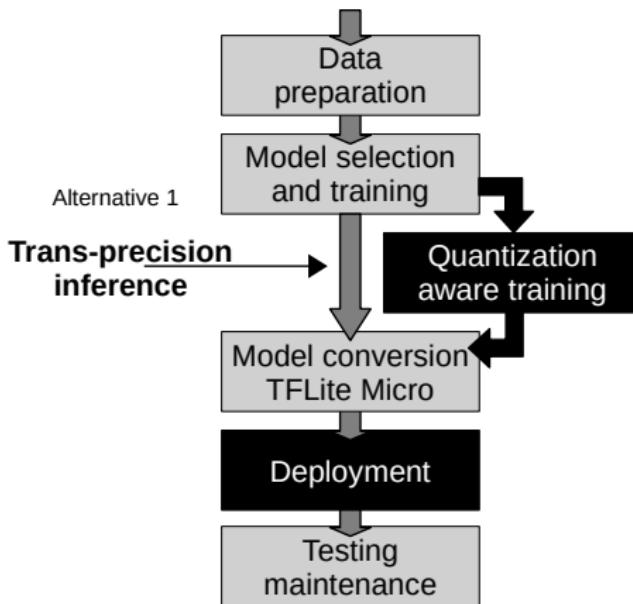
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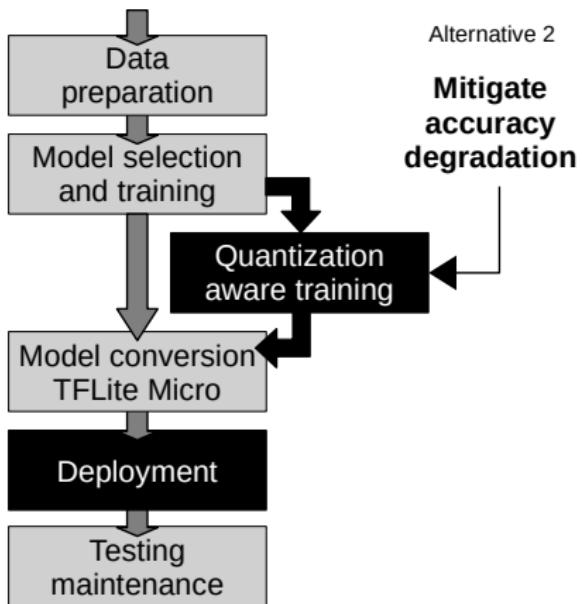
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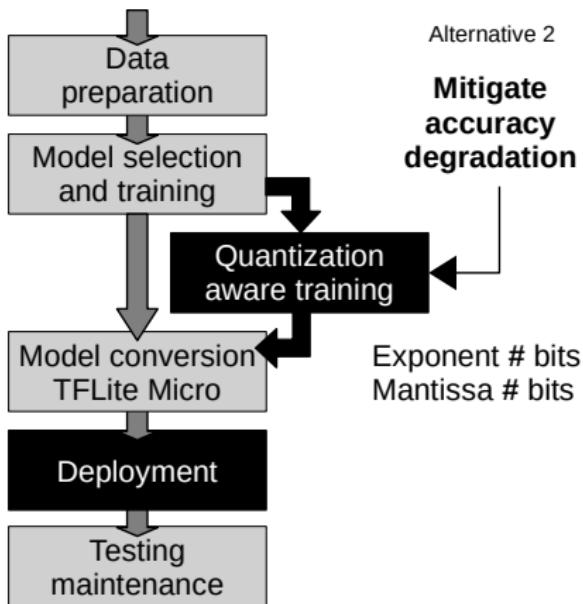
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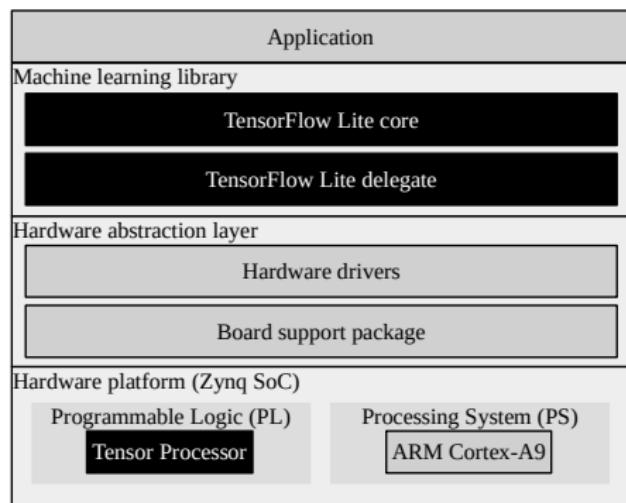
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HW/SW co-design framework



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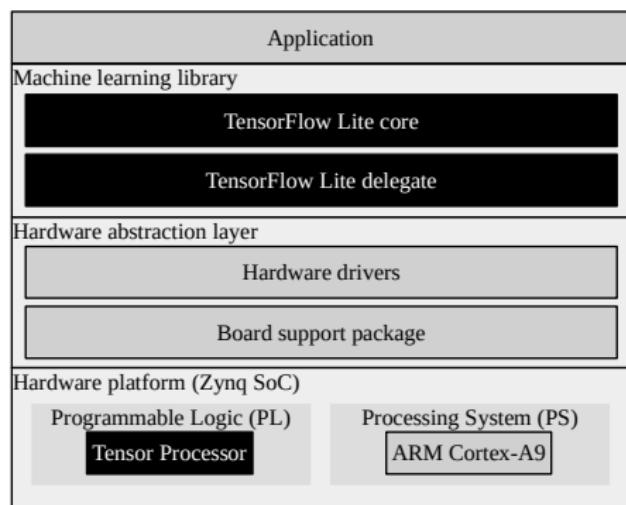
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Industry standard framework

HW/SW co-design framework



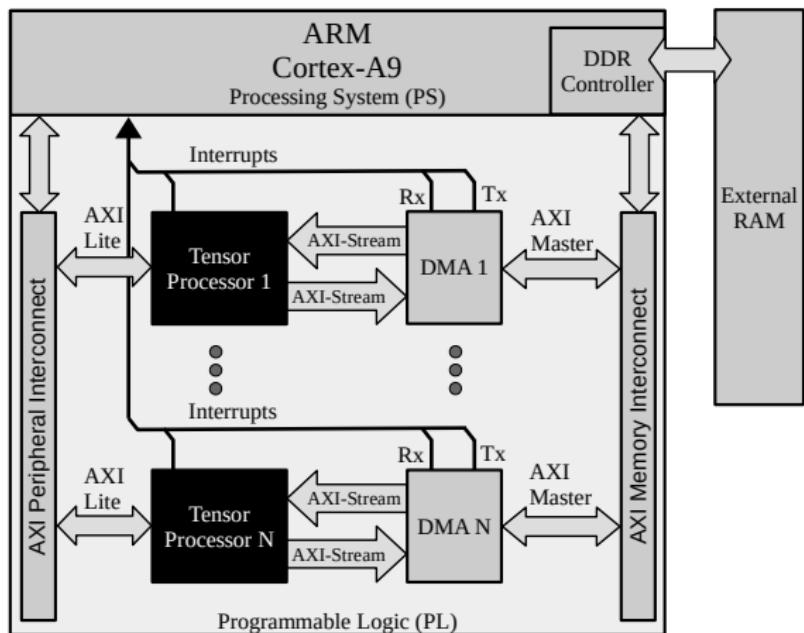
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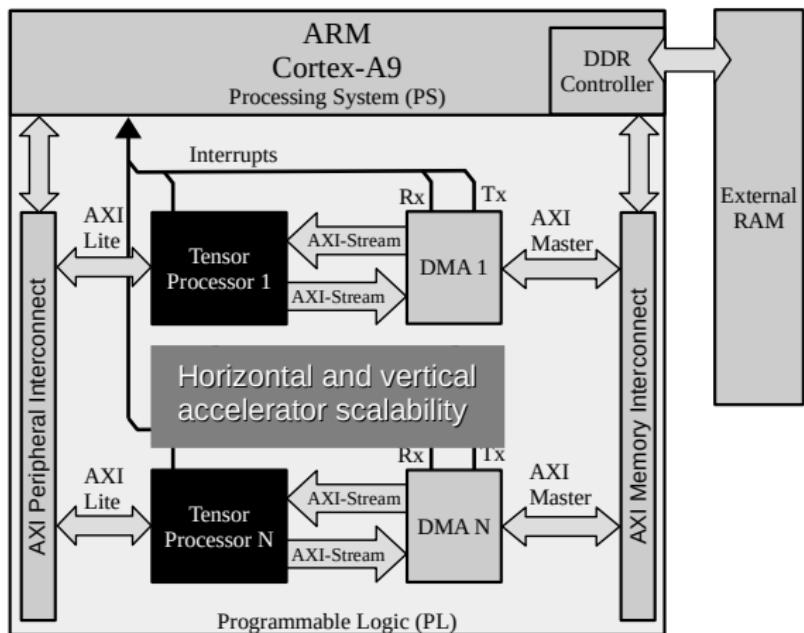
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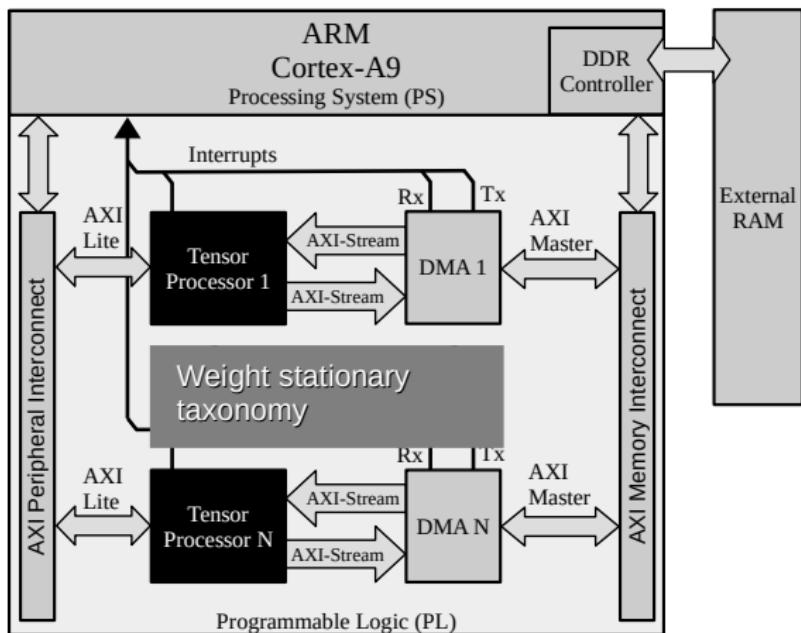
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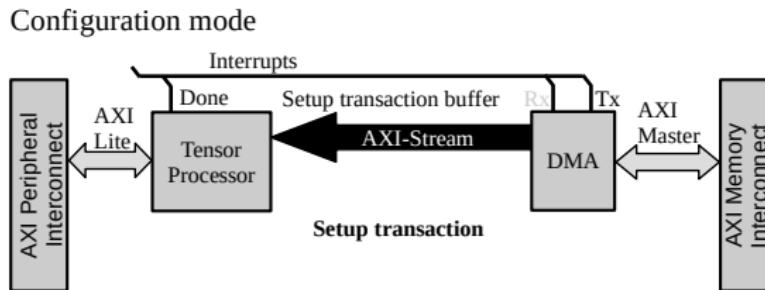
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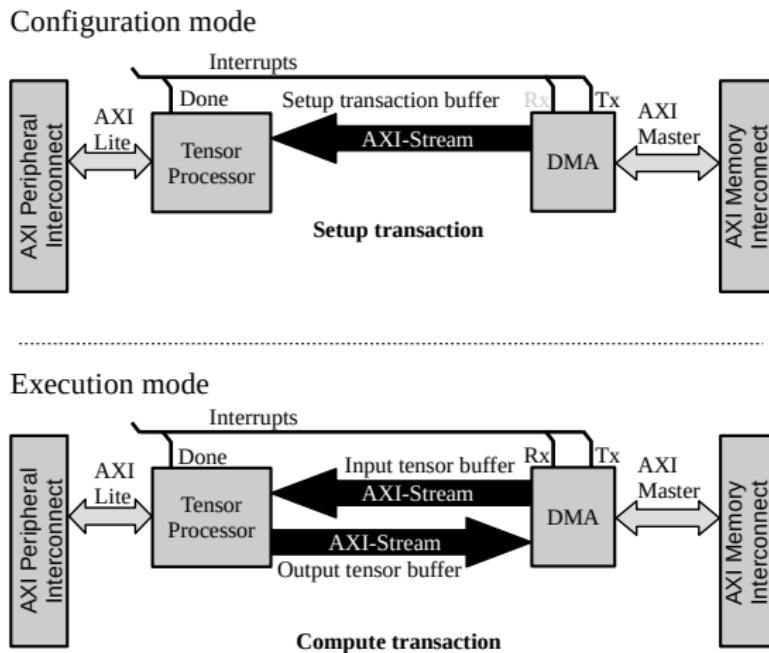
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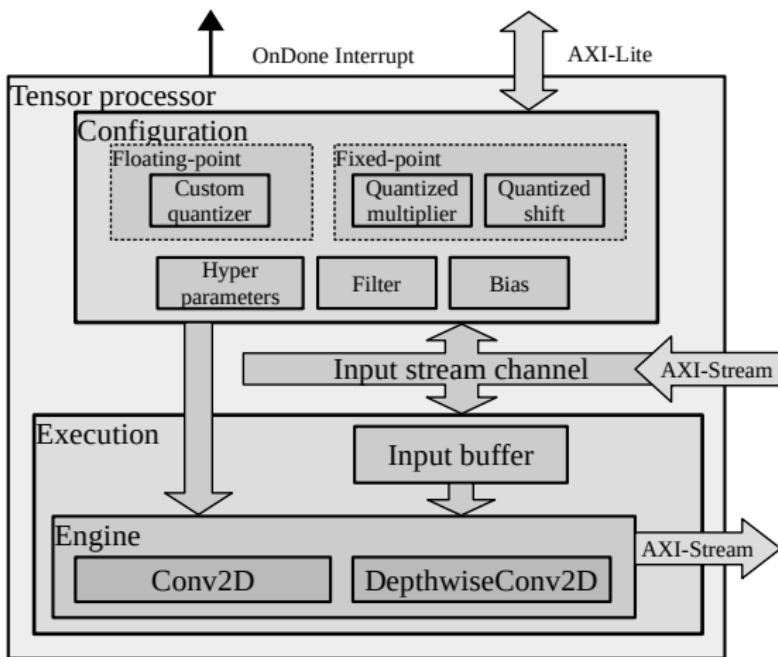
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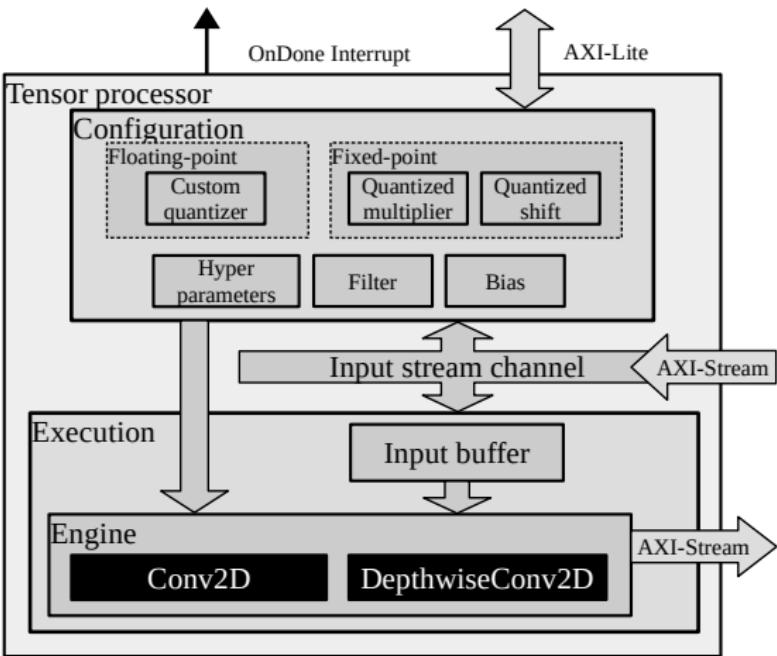
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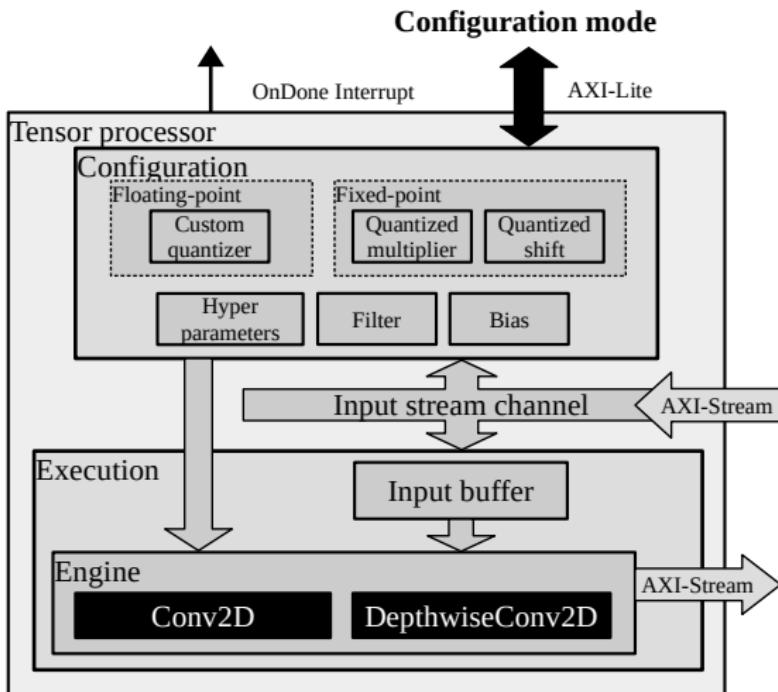
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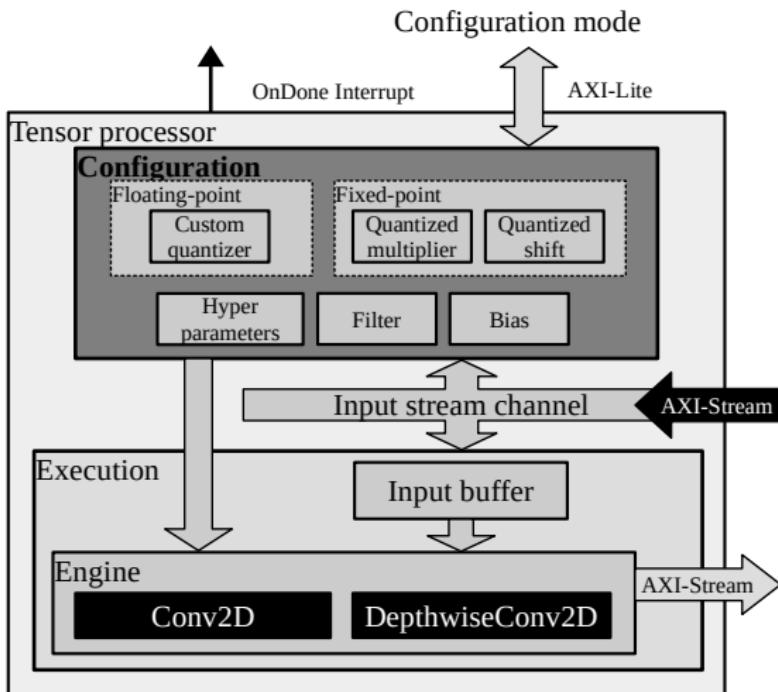
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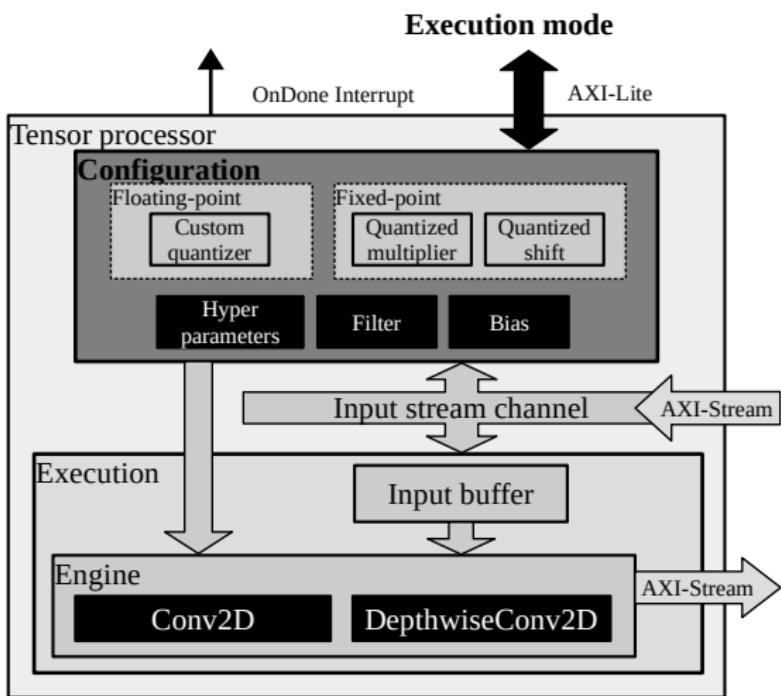
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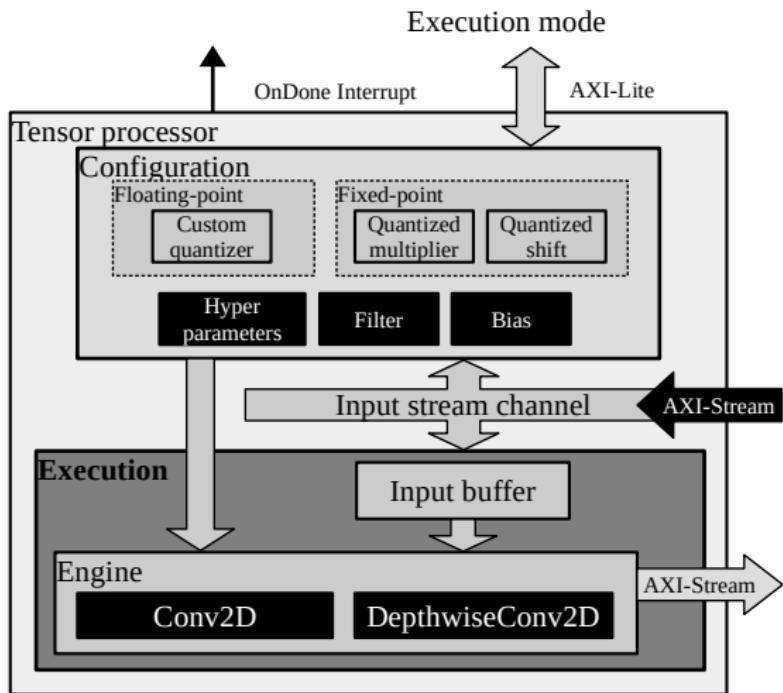
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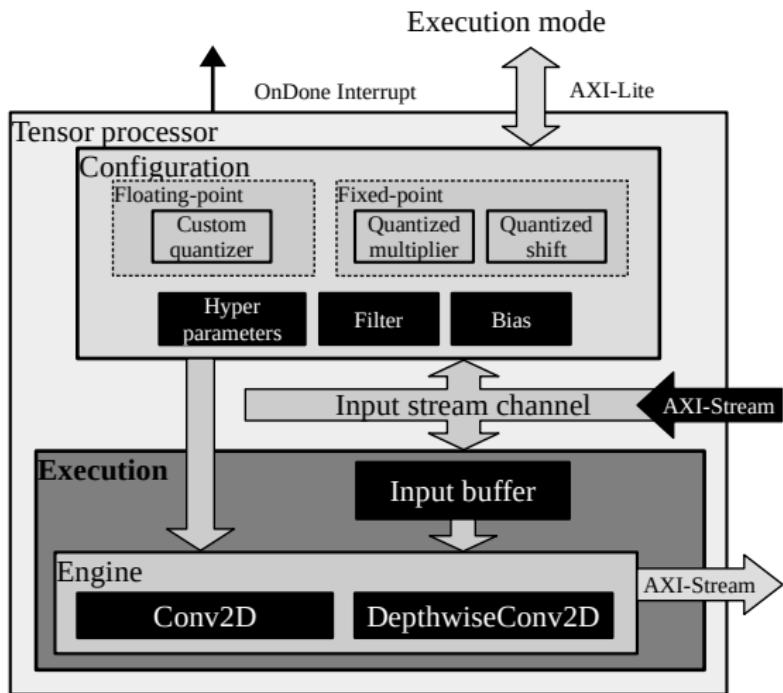
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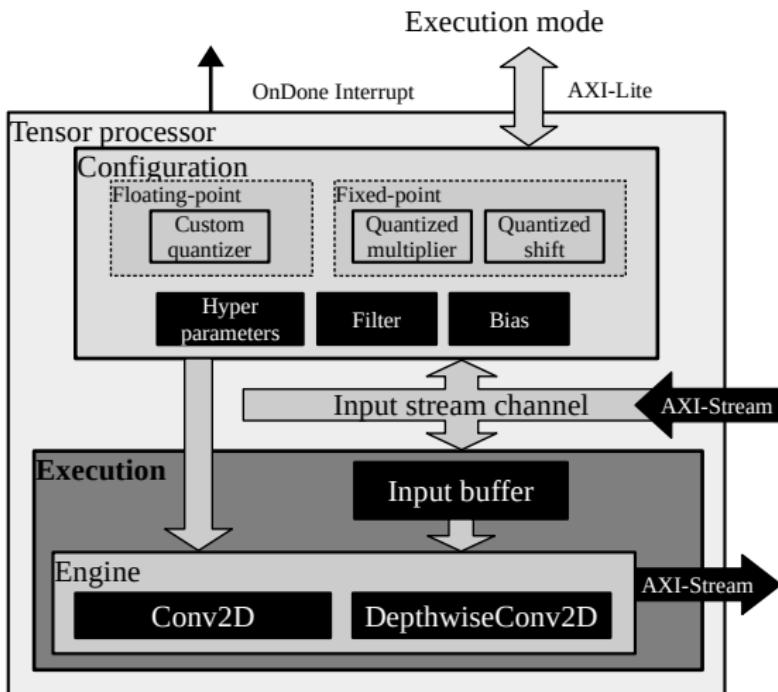
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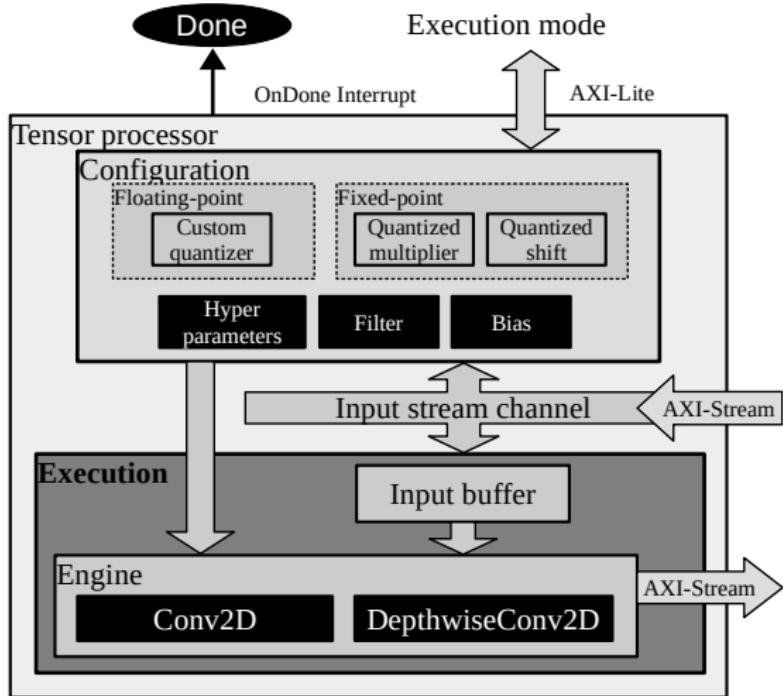
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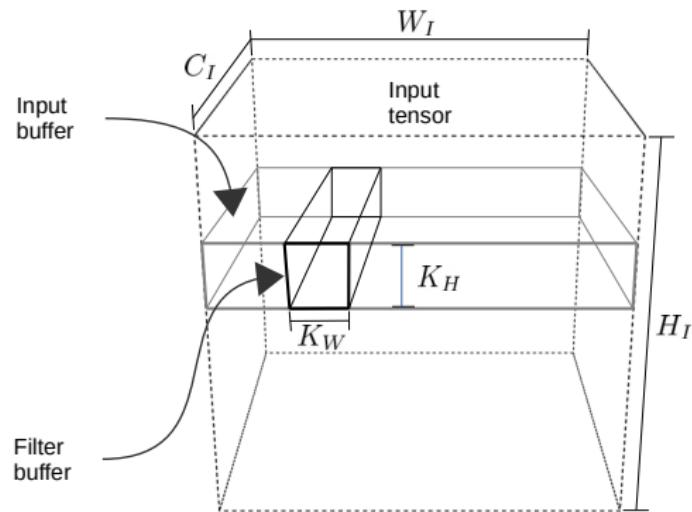
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$$Conv2D(W, b, h)_{i,j,o} = \sum_{k,l,m} h_{(i+k, j+l, m)} W_{(o, k, l, m)} + b_o$$

Methodology

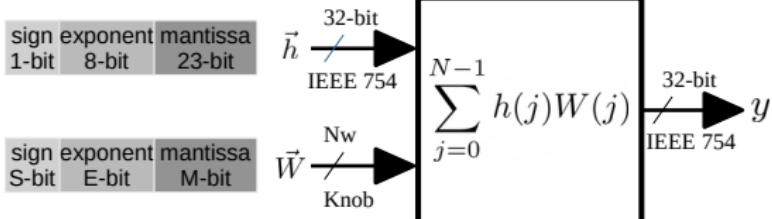
Trans-Precision Neural Network Deployment for Low-Power Embedded Systems

The methodology efficiently deploys and accelerates floating-point neural networks on embedded systems, optimizing performance, energy consumption, and hardware utilization.

Abstraction levels:

Multiply-Accumulate Unit
Hybrid Custom floating-point computation

1. Model deployment



2. System infrastructure

3. Streamlined acceleration

4. Optimized processing

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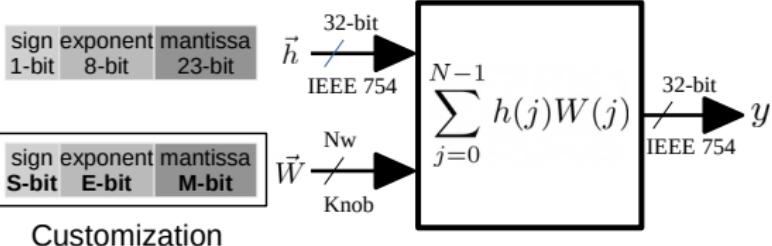
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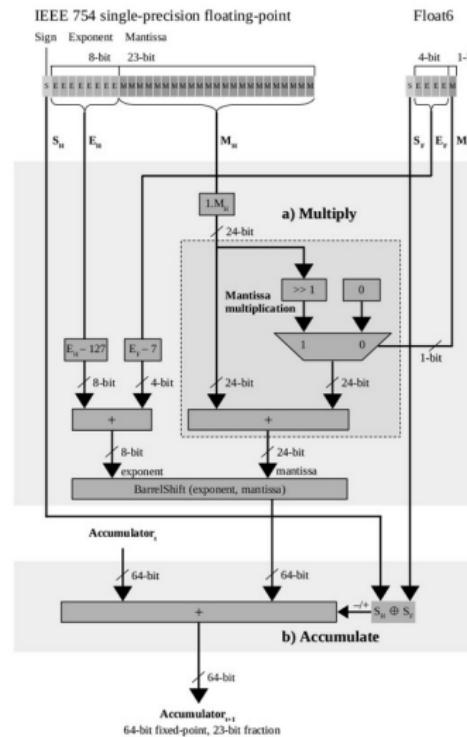
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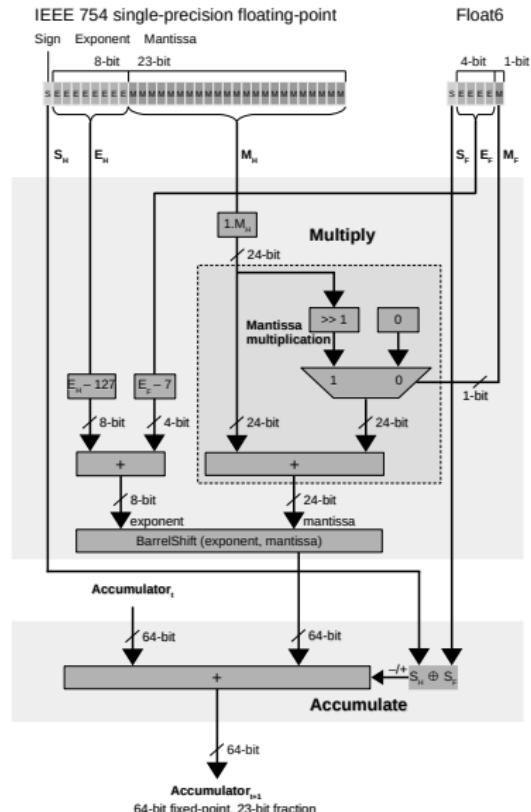
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Custom Floating-Point MAC Designs

Hybrid Custom Floating-Point Multiply-Accumulate Unit



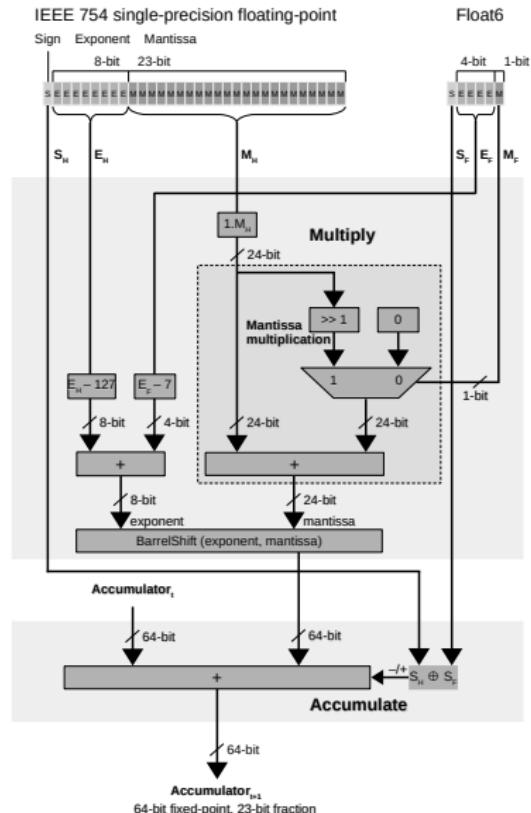
Custom Floating-Point MAC Designs

Hybrid Custom Floating-Point Multiply-Accumulate Unit

Vector dot-product:

Multiplication

Accumulation



Custom Floating-Point MAC Designs

Hybrid Custom Floating-Point Multiply-Accumulate Unit

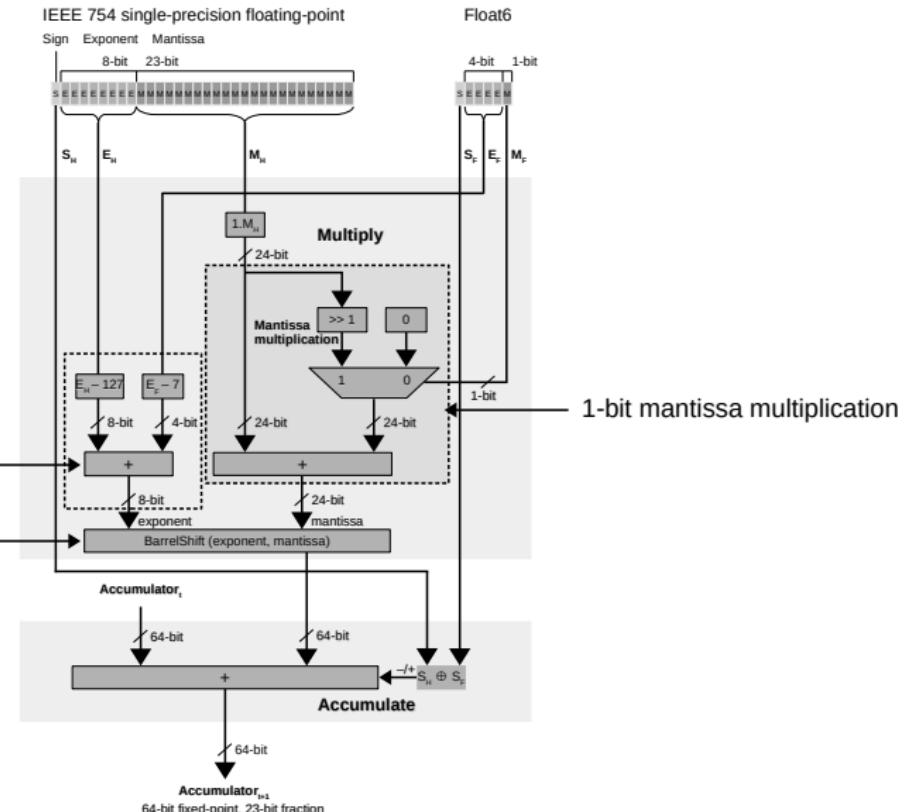
Vector dot-product:

Multiplication

Accumulation

Exponent addition

Denormalization



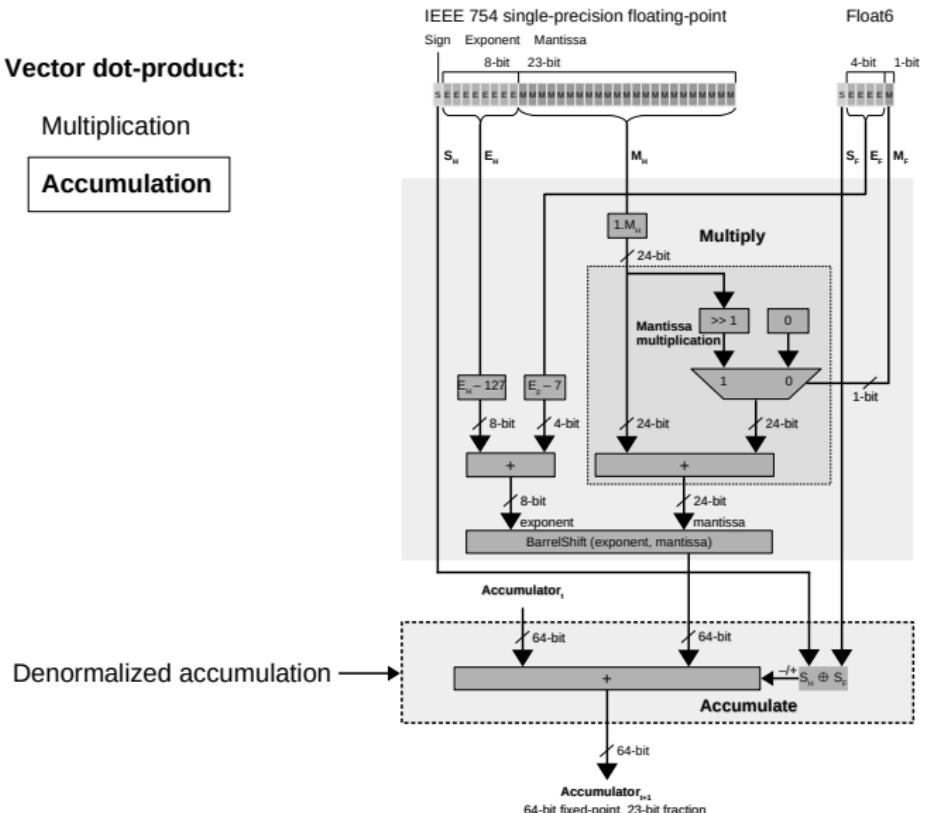
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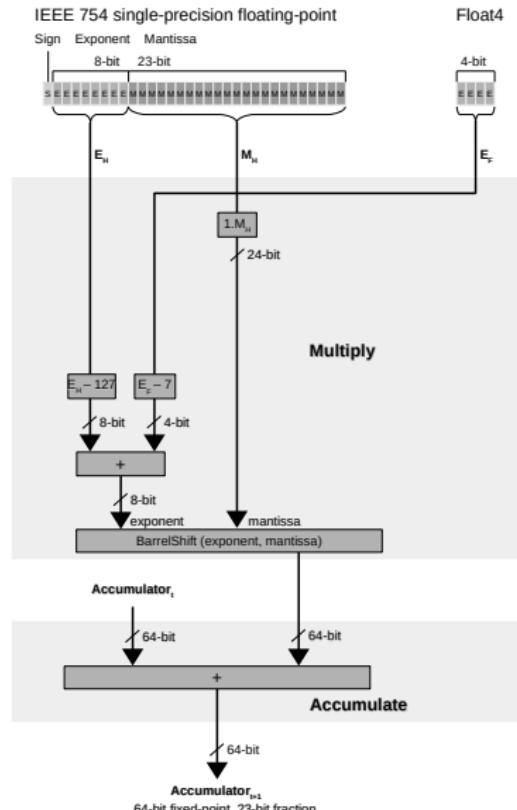
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Custom Floating-Point MAC Designs

Hybrid Custom Floating-Point Multiply-Accumulate Unit



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Hybrid Custom Floating-Point Multiply-Accumulate Unit

For noise-robust applications with non-negativity constraints.

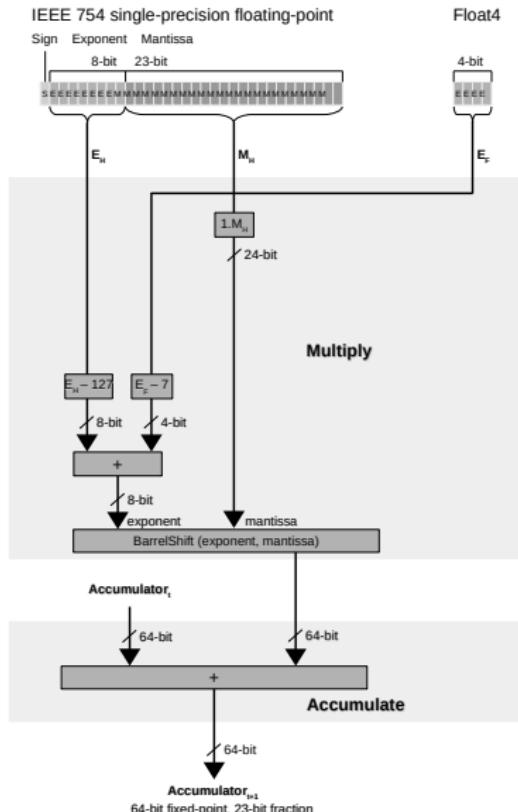
Non-negative Tensor Factorization

Non-negative Sparse Coding

Non-negative Matrix Factorization

Spike-by-Spike Neural Networks

Etc.



Custom Floating-Point Quantization

Algorithm 1: Custom floating-point quantization

```
Input: MODEL as the CNN
Input: Esize as the target exponent bit size
Input: Msize as the target mantissa bits size
Input: STDMsize as the IEEE 754 mantissa bit size
Output: MODEL as the quantized CNN

1 foreach layer in MODEL do
2   if layer is Conv2D or SeparableConv2D then
3     filter, bias ← GetWeights(layer)
4     foreach x in filter and bias do
5       sign ← GetSign(x)
6       exp ← GetExponent(x)
7       fullexp ← 2Esize-1 - 1 // Get full range value
8       cman ← GetCustomMantissa(x, Msize)
9       leftman ← GetLeftoverMantissa(x, Msize)
10      if exp < -fullexp then
11        x ← 0
12      else
13        if exp > fullexp then
14          x ← (-1)sign · 2fullexp · (1 + (1 - 2-Msize))
15        else
16          if 2STDMsize-Msize-1 - 1 < leftman then
17            cman ← cman + 1 // Above halfway
18            if 2Msize - 1 < cman then
19              cman ← 0 // Correct mantissa overflow
20              exp ← exp + 1
21            x ← (-1)sign · 2exp · (1 + cman · 2-Msize)
22      SetWeights(layer, filter, bias)
```

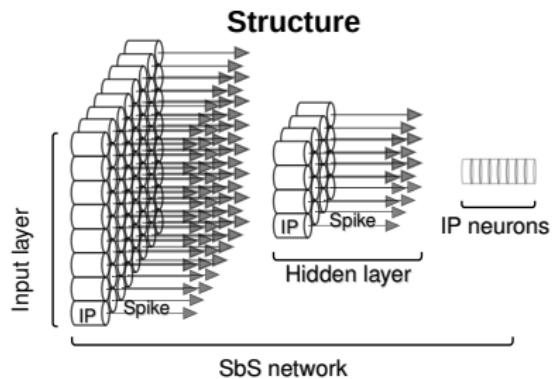
1 Methodology

2 Custom Floating-Point MAC Designs and Quantization Techniques

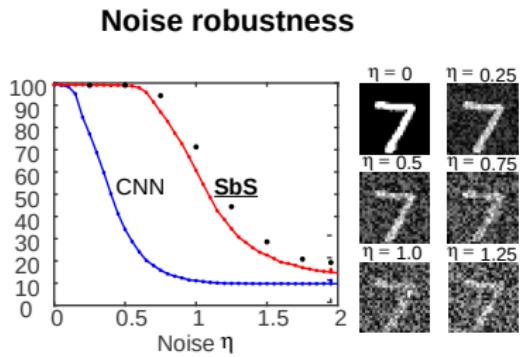
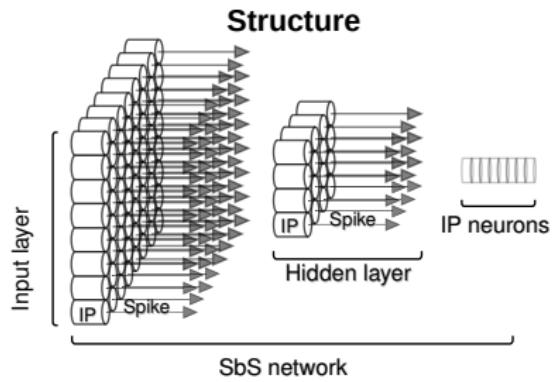
3 Case Studies

4 Conclusions

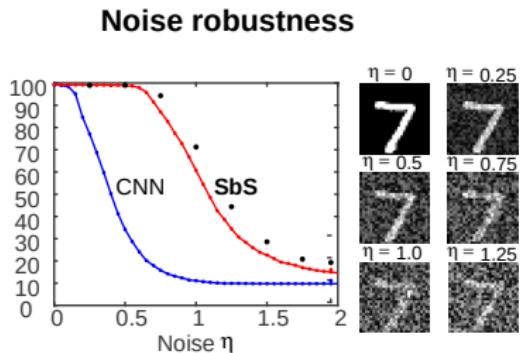
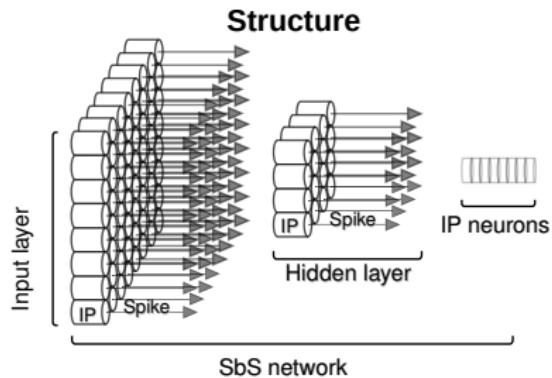
Spike-by-Spike Neural Network



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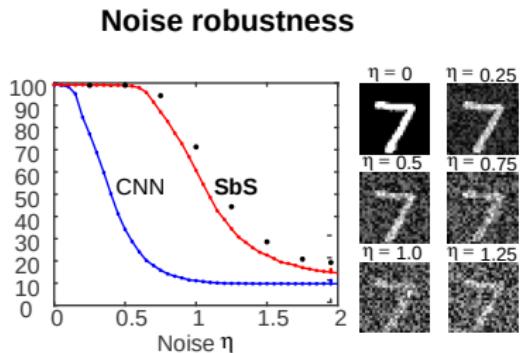
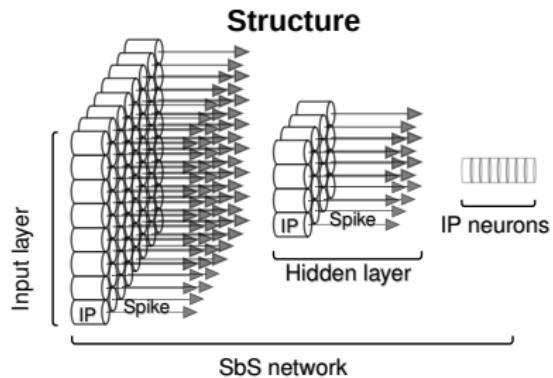
Spike-by-Spike Neural Network



Neuron update

$$h_{\mu}^{new}(i) = \frac{1}{1 + \epsilon} \left(h_{\mu}(i) + \epsilon \frac{h_{\mu}(i)W(s_t|i)}{\sum_j h_{\mu}(j)W(s_t|j)} \right)$$

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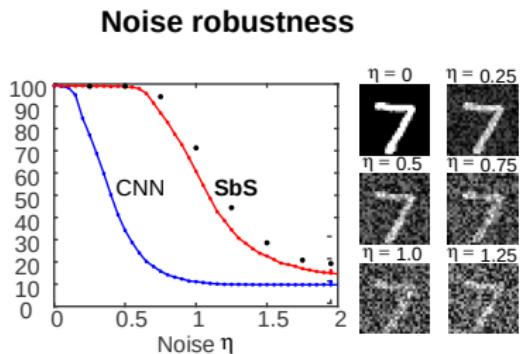
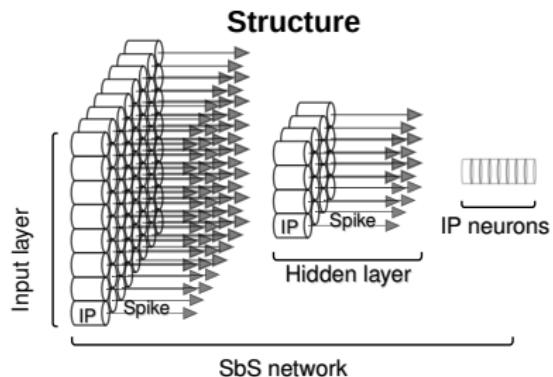


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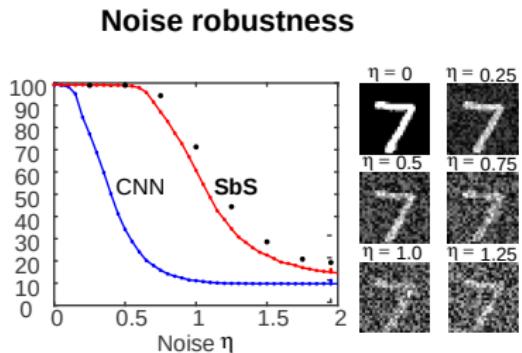
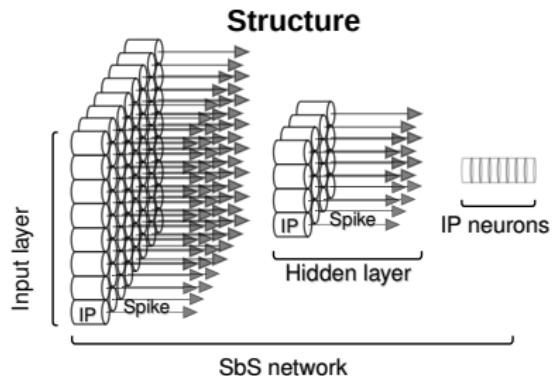
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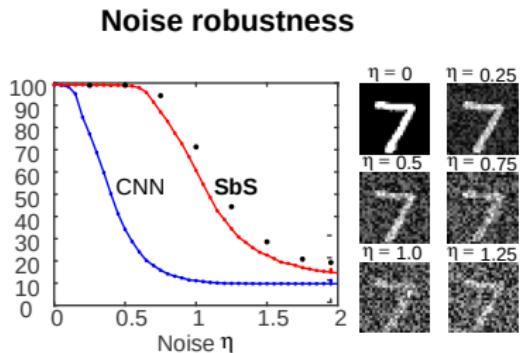
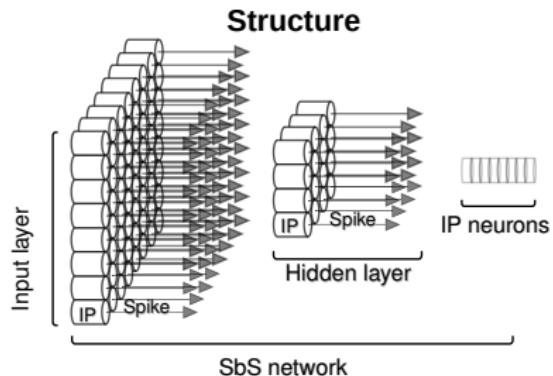
- Noise robustness
- Iterative optimization
- No sign bit required
- Requires division
- Compute and memory intensive

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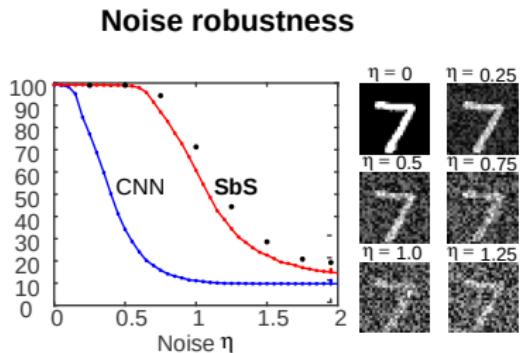
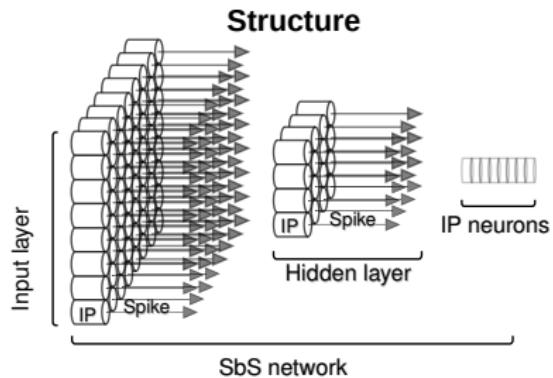
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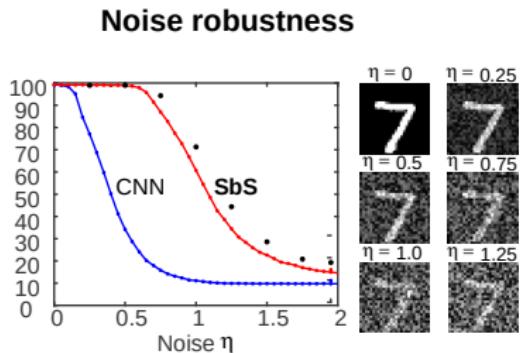
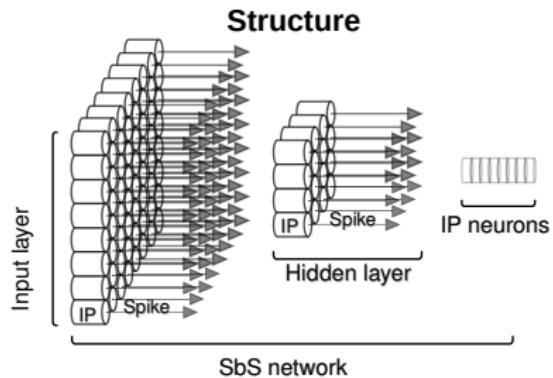
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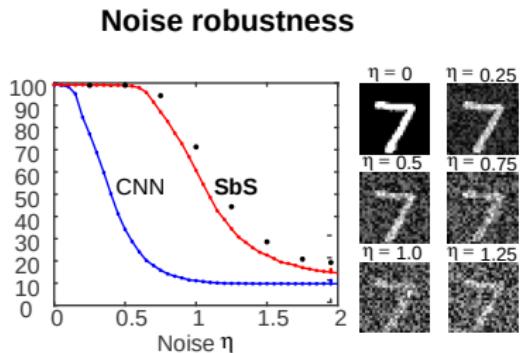
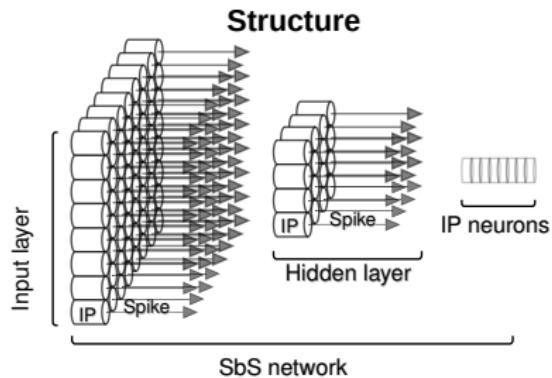
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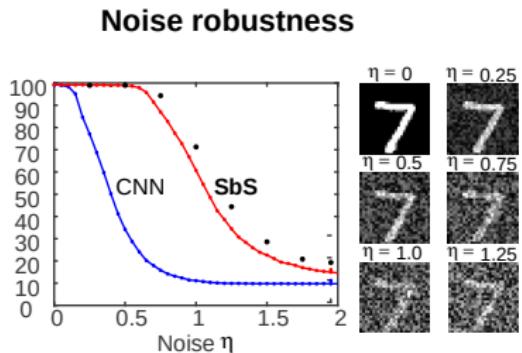
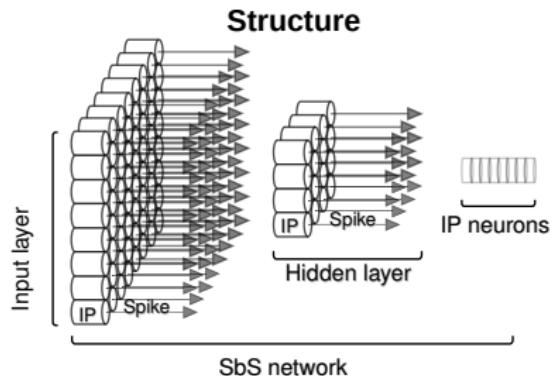
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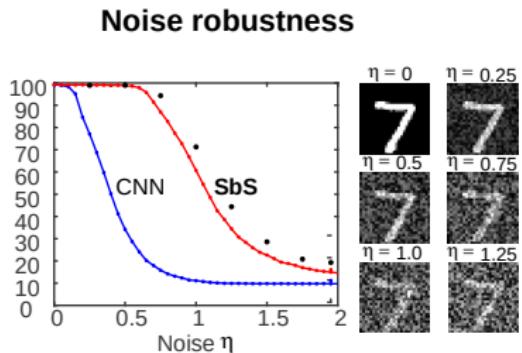
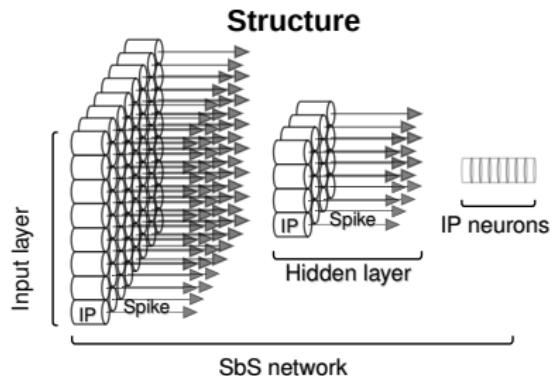
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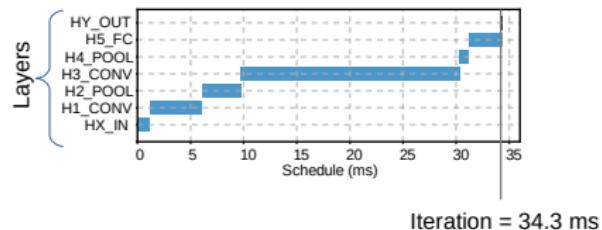
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Deployment

Floating-point 32-bit

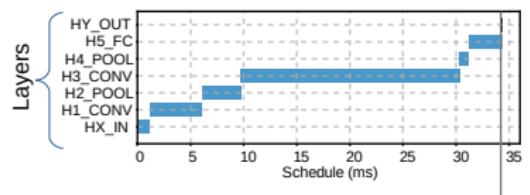
ARM Cortex A9 @ 666 MHz



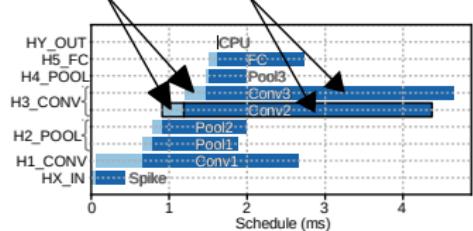
Deployment

Floating-point 32-bit

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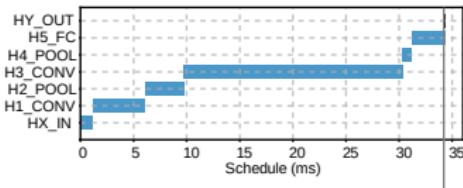
CPU Accelerator Iteration = 34.3 ms



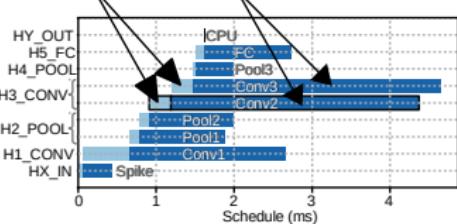
Deployment

Floating-point 32-bit

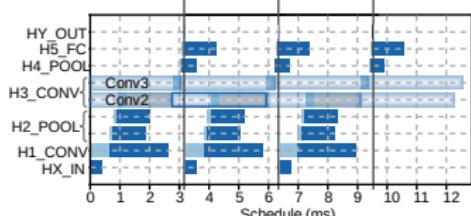
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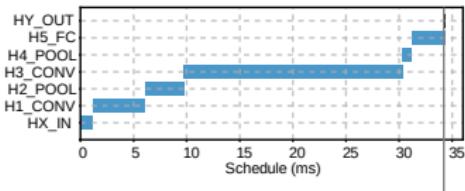
Iteration = 3.18 ms



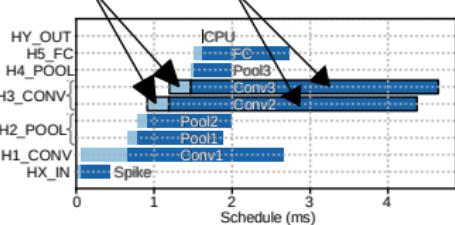
Deployment

Floating-point 32-bit

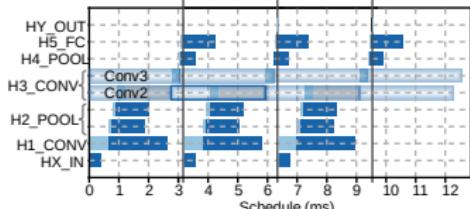
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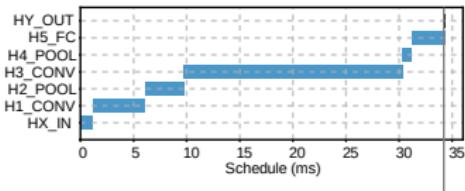
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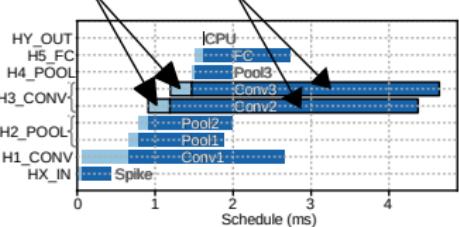
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Floating-point 32-bit

ARM Cortex A9 @ 666 MHz

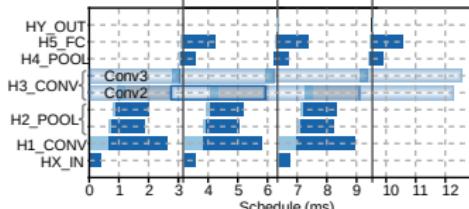


CPU Accelerator Iteration = 34.3 ms



Acceleration = 10.7

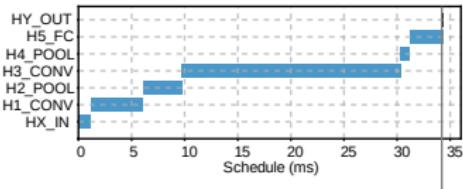
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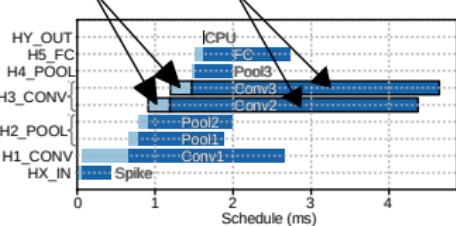
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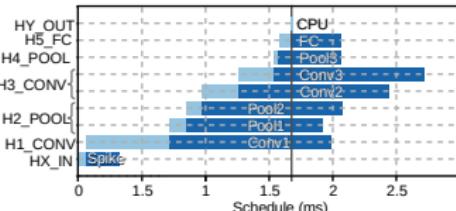
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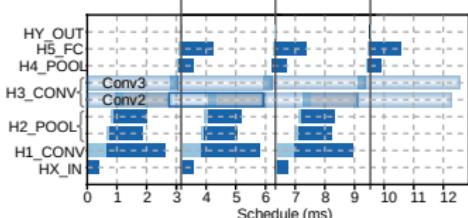


Hybrid logarithmic 4-bit

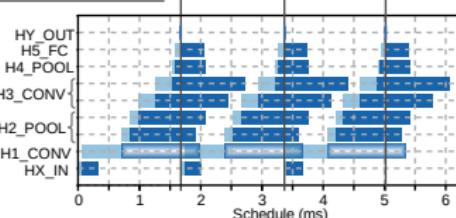


Acceleration = 10.7

Iteration = 3.18 ms



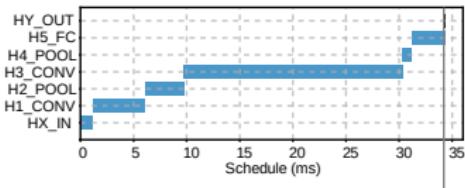
Iteration = 1.67 ms



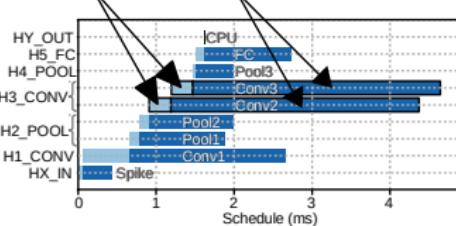
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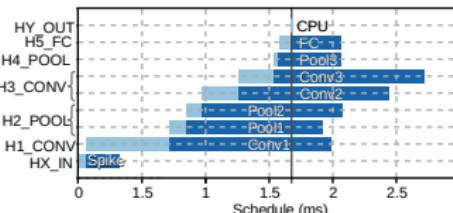
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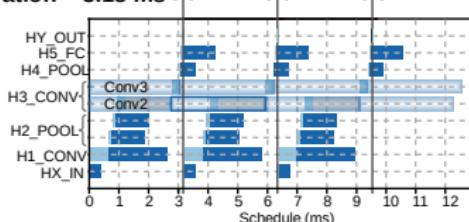
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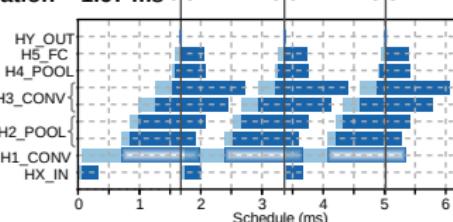
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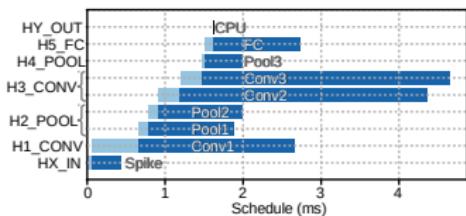


Acceleration = 20.5 Iteration = 1.67 ms

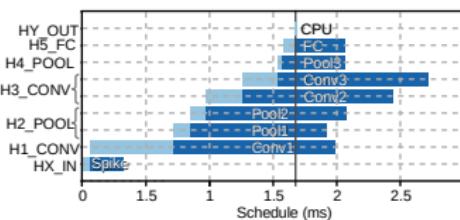


Deployment

Standard floating-point

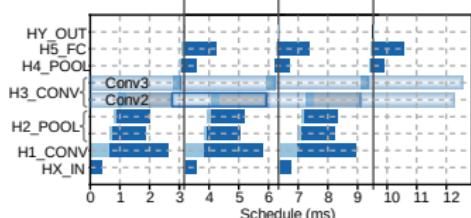


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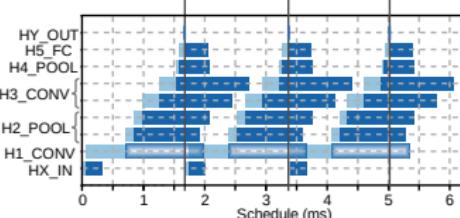
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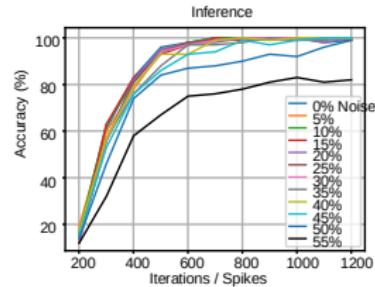
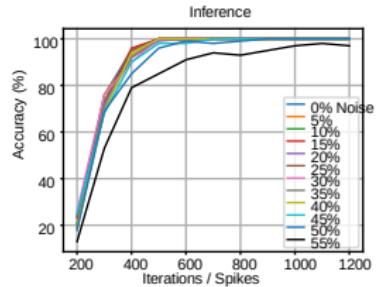
Iteration = 1.67 ms

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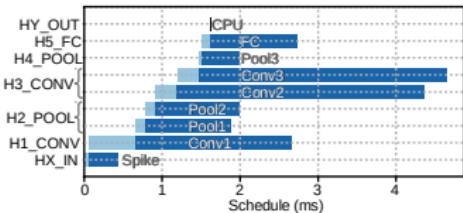


Accelerating Spike-by-Spike Neural Networks with Hybrid Logarithmic 4-bit

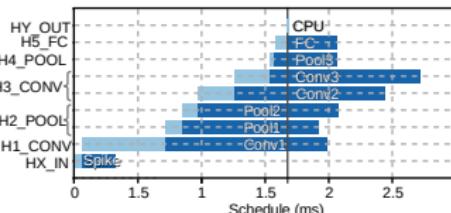
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Standard floating-point

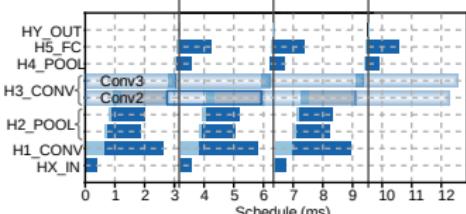


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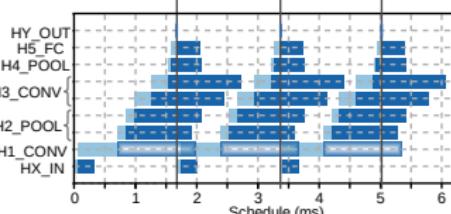
Acceleration = 10.7

Iteration = 3.18 ms



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Iteration = 1.67 ms



Boosting TinyML Performance with Hybrid Floating-Point 6-bit

TinyML Application: CNN Sensor Analytics for Structural Health Monitoring

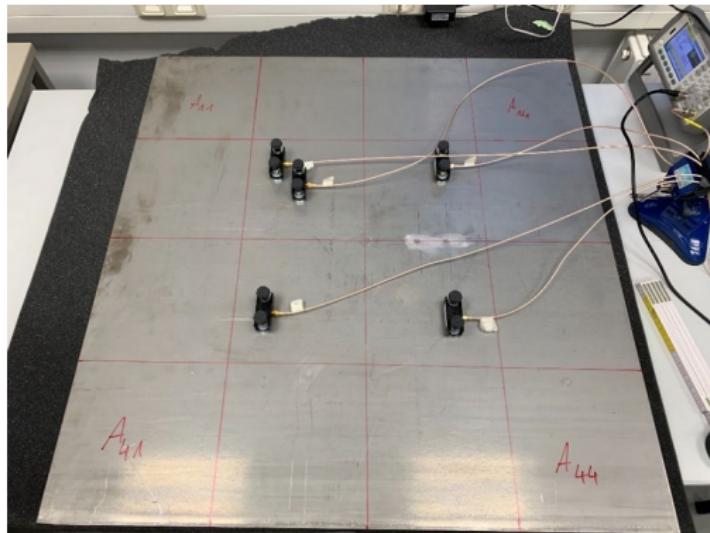
Experimental setup:

Sensor and noise positions

Training dataset

Testing dataset

Model architecture



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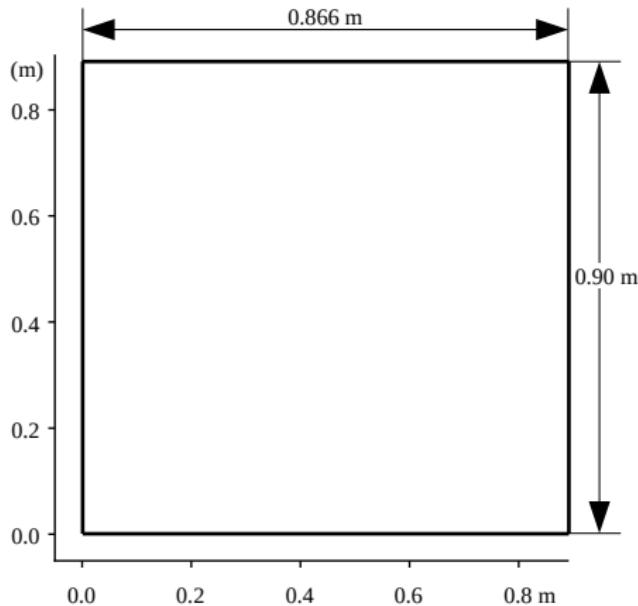
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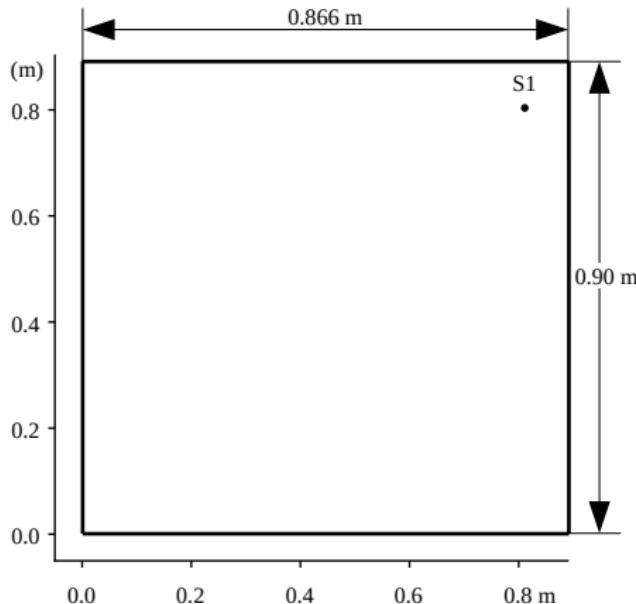
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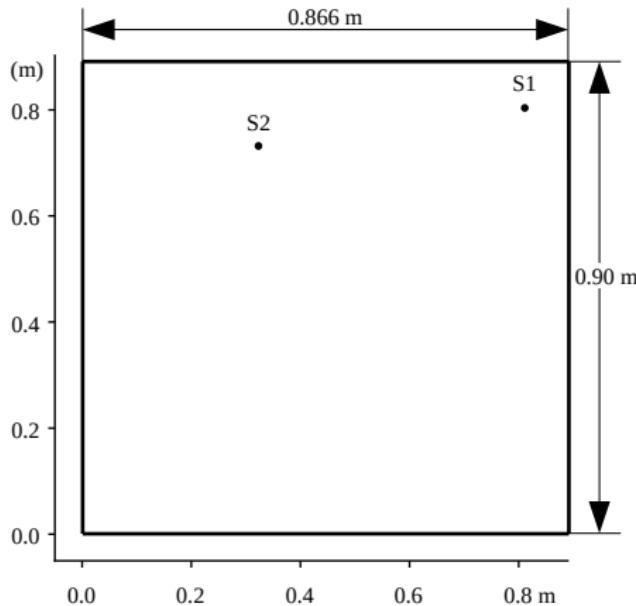
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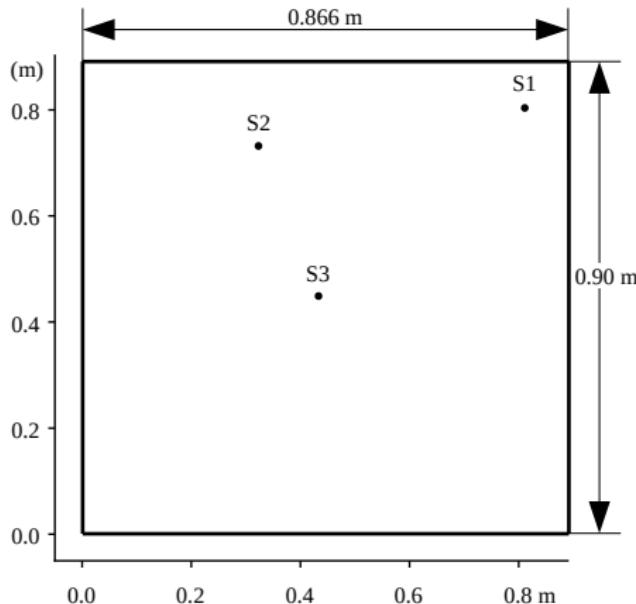
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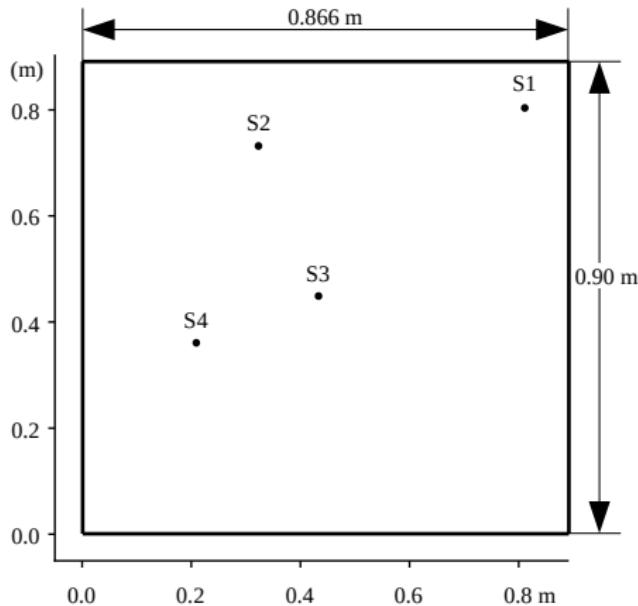
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Boosting TinyML Performance with Hybrid Floating-Point 6-bit

TinyML Application: CNN Sensor Analytics for Structural Health Monitoring

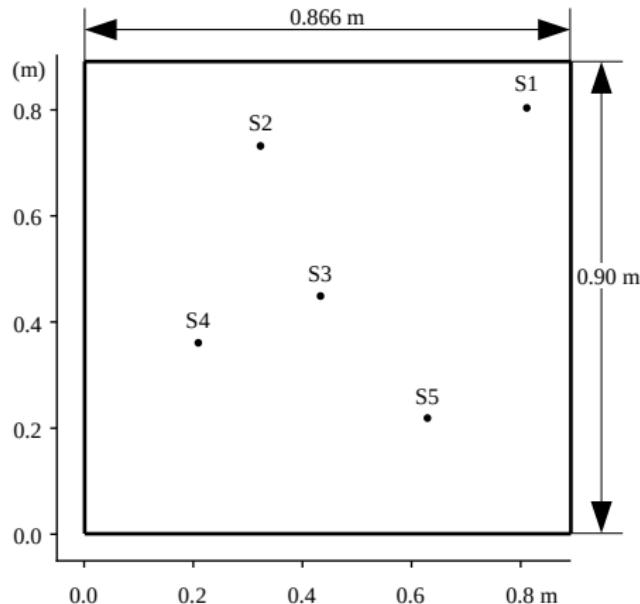
Experimental setup:

Sensor and noise positions

Training dataset

Testing dataset

Model architecture



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TinyML Application: CNN Sensor Analytics for Structural Health Monitoring

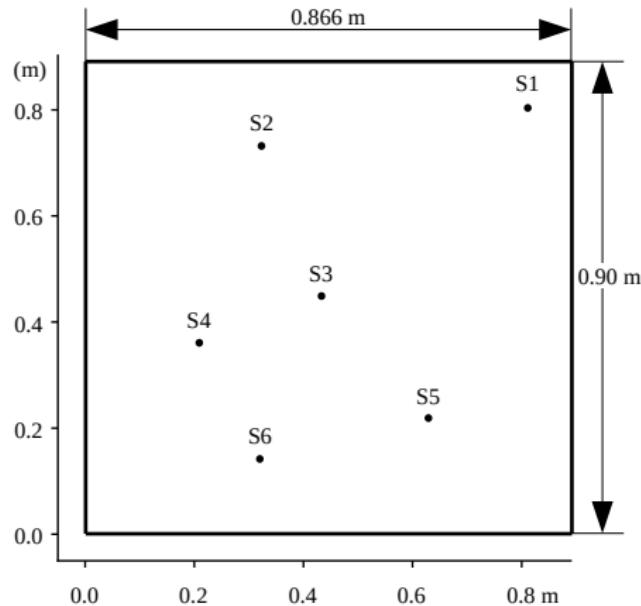
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TinyML Application: CNN Sensor Analytics for Structural Health Monitoring

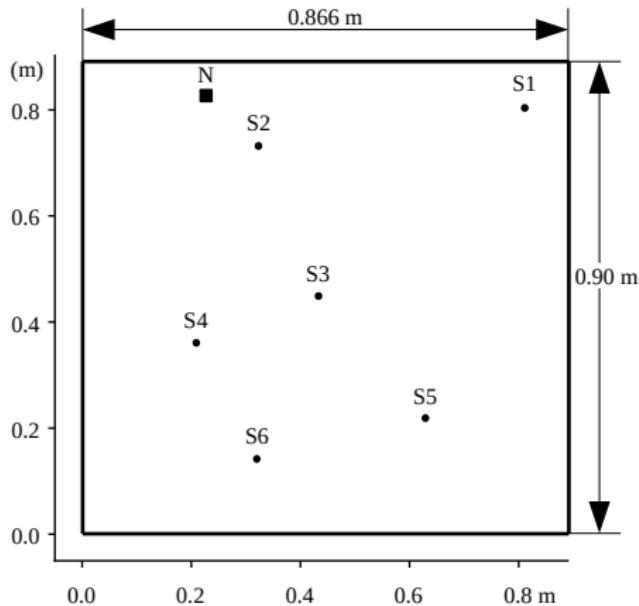
Experimental setup:

Sensor and noise positions

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Model architecture



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TinyML Application: CNN Sensor Analytics for Structural Health Monitoring

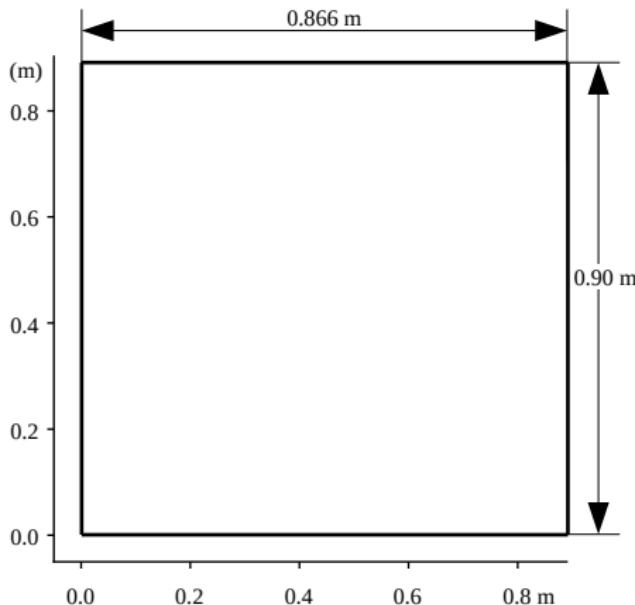
Experimental setup:

Sensor and noise positions

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Model architecture



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TinyML Application: CNN Sensor Analytics for Structural Health Monitoring

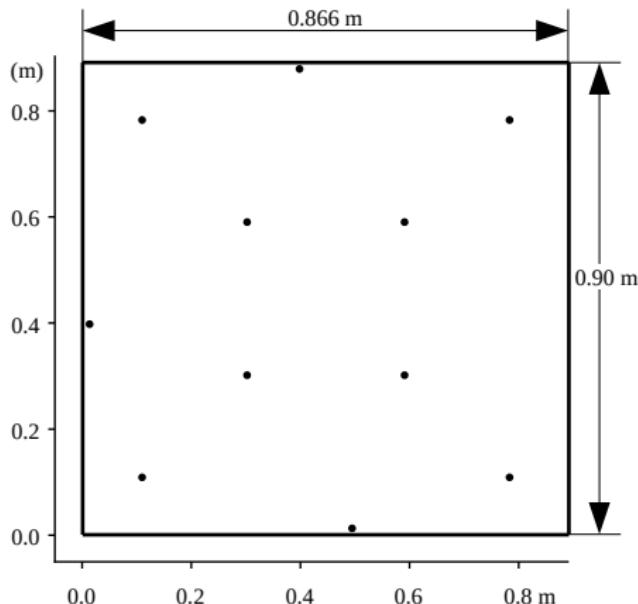
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TinyML Application: CNN Sensor Analytics for Structural Health Monitoring

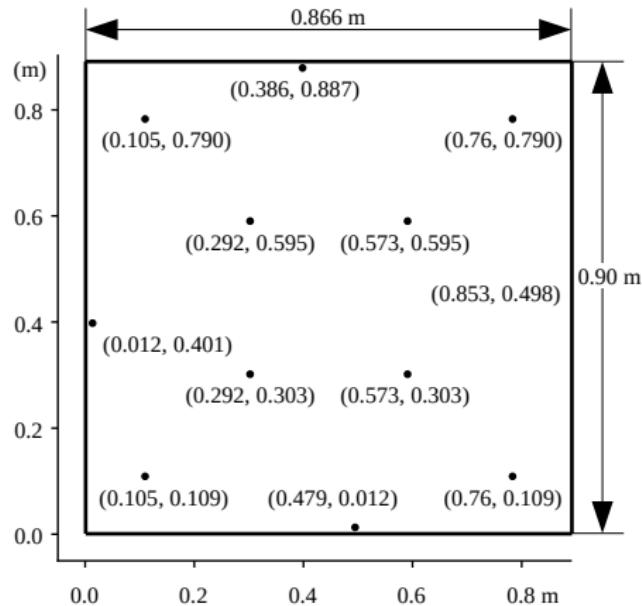
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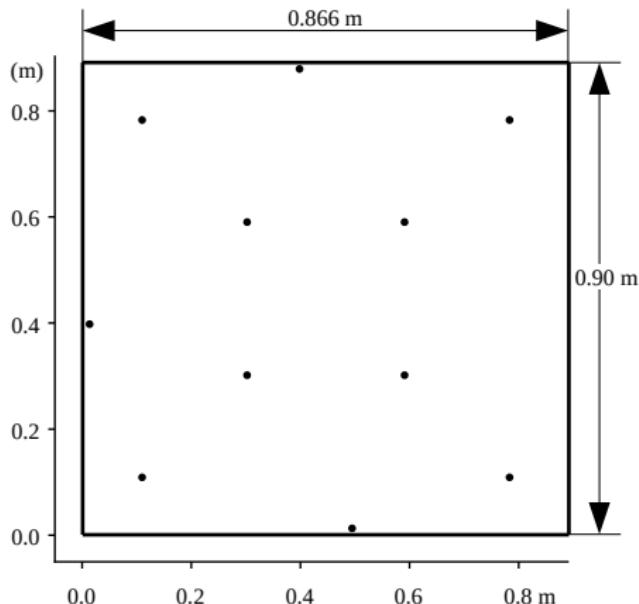
Experimental setup:

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Training dataset

Testing dataset

Model architecture



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TinyML Application: CNN Sensor Analytics for Structural Health Monitoring

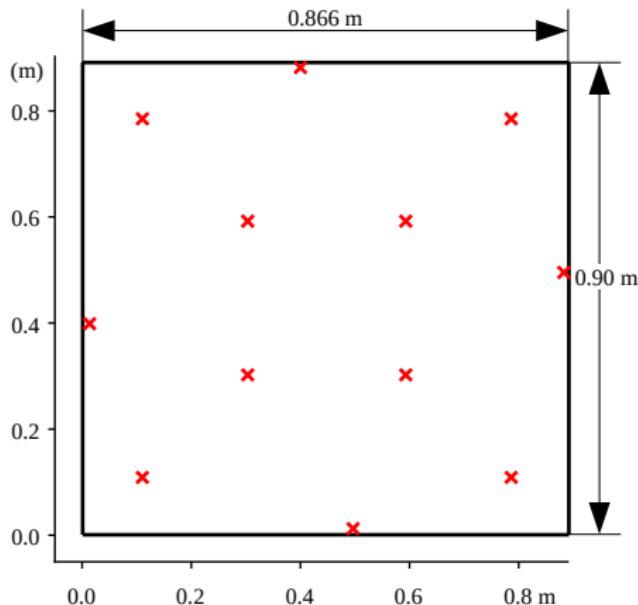
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Training dataset

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TinyML Application: CNN Sensor Analytics for Structural Health Monitoring

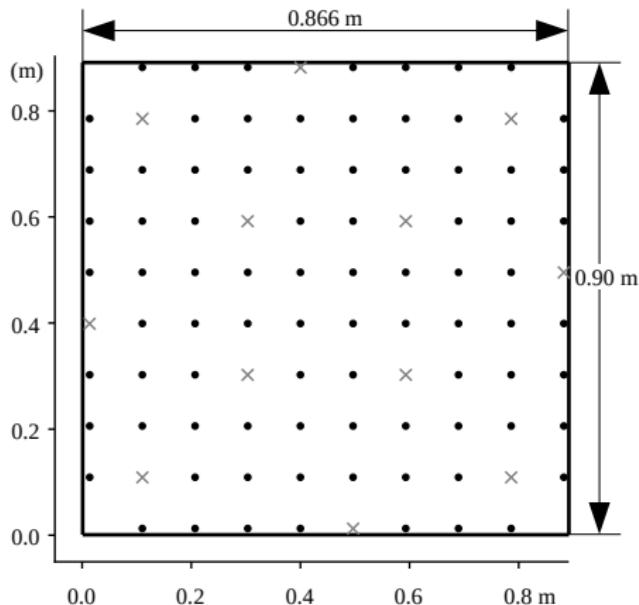
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Testing dataset

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TinyML Application: CNN Sensor Analytics for Structural Health Monitoring

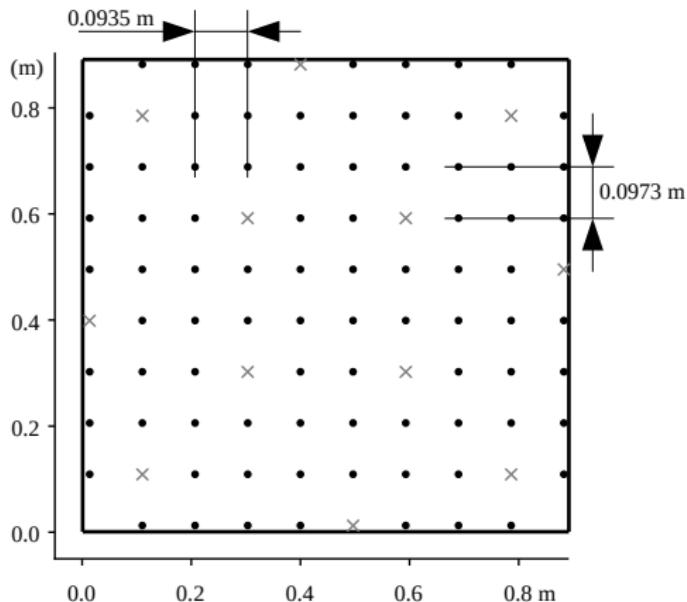
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Training dataset

Testing dataset

Model architecture



Boosting TinyML Performance with Hybrid Floating-Point 6-bit

TinyML Application: CNN Sensor Analytics for Structural Health Monitoring

Experimental setup:

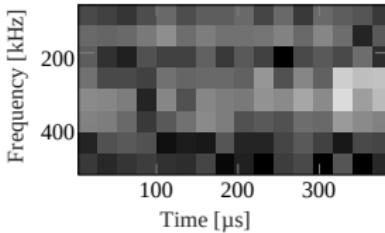
Sensor and noise positions

Training dataset

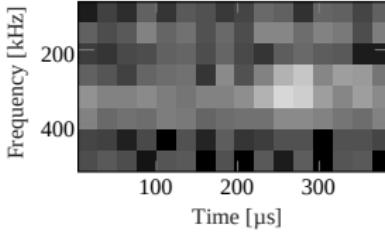
Testing dataset

Model architecture

S1



S2



Boosting TinyML Performance with Hybrid Floating-Point 6-bit

TinyML Application: CNN Sensor Analytics for Structural Health Monitoring

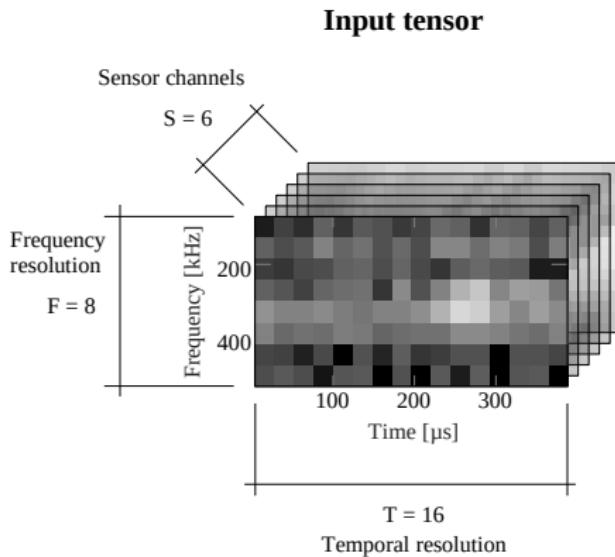
Experimental setup:

Sensor and noise positions

Training dataset

Testing dataset

Model architecture



Boosting TinyML Performance with Hybrid Floating-Point 6-bit

TinyML Application: CNN Sensor Analytics for Structural Health Monitoring

Experimental setup:

Sensor and noise positions

Training dataset

Testing dataset

Model architecture

CNN-regression model

Output tensor (x, y)

FC (2), Linear
FC (E = 64), ReLu
FC (D = 196), ReLu
Flatten
2 x 2 MaxPool, stride 2
BatchNormalization
3 x 3 Conv (C = 60), ReLu
2 x 2 MaxPool, stride 2
BatchNormalization
3 x 3 Conv (B = 55), ReLu
2 x 2 MaxPool, stride 2
BatchNormalization
3 x 3 Conv (A = 50), ReLu
Input tensor (F x T x S)

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TinyML Application: CNN Sensor Analytics for Structural Health Monitoring

Experimental setup:

Sensor and noise positions

Training dataset

Testing dataset

Model architecture

CNN-regression model

Output tensor (x, y)

FC (2), Linear	
FC (E = 64), ReLu	
FC (D = 196), ReLu	
Flatten	
2 x 2 MaxPool, stride 2	
BatchNormalization	
3 x 3 Conv (C = 60), ReLu	Conv_c
2 x 2 MaxPool, stride 2	
BatchNormalization	
3 x 3 Conv (B = 55), ReLu	Conv_B
2 x 2 MaxPool, stride 2	
BatchNormalization	
3 x 3 Conv (A = 50), ReLu	Conv_A
Input tensor (F x T x S)	

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TinyML Application: CNN Sensor Analytics for Structural Health Monitoring

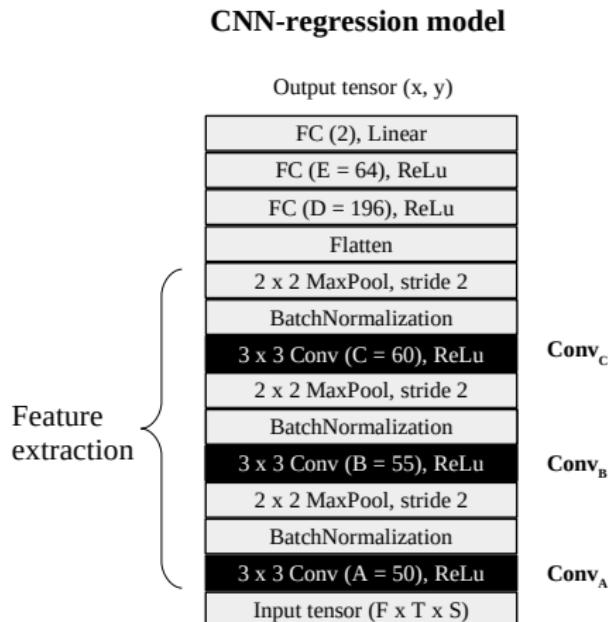
Experimental setup:

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Training dataset

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TinyML Application: CNN Sensor Analytics for Structural Health Monitoring

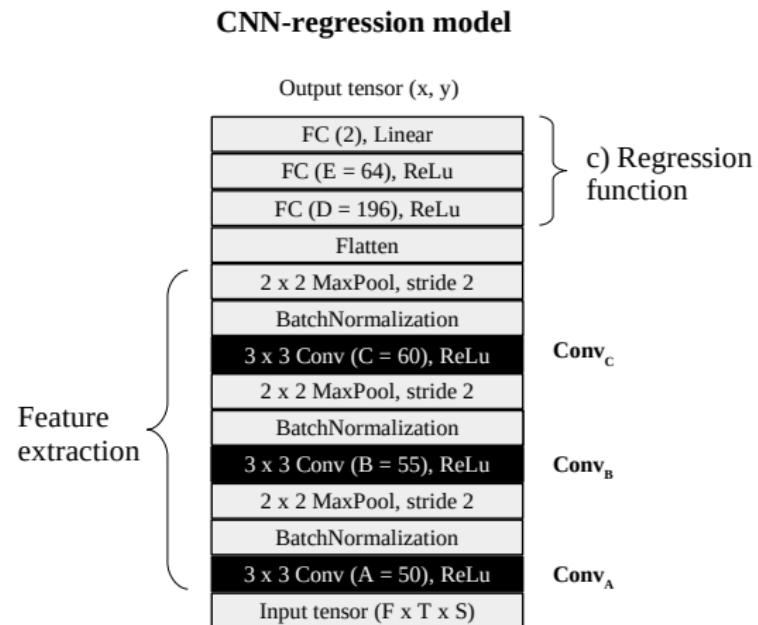
Experimental setup:

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Model architecture



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TinyML Application: CNN Sensor Analytics for Structural Health Monitoring

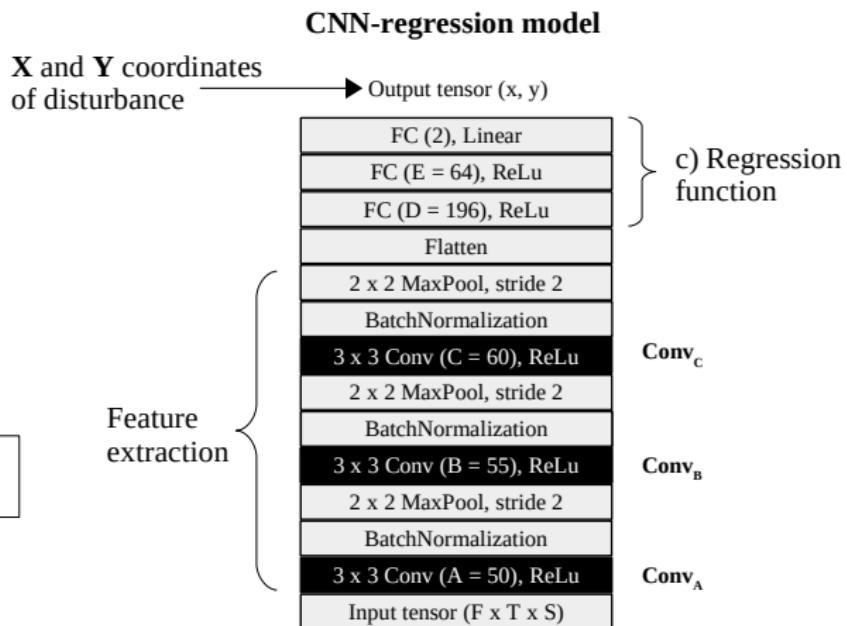
Experimental setup:

Sensor and noise positions

Training dataset

Testing dataset

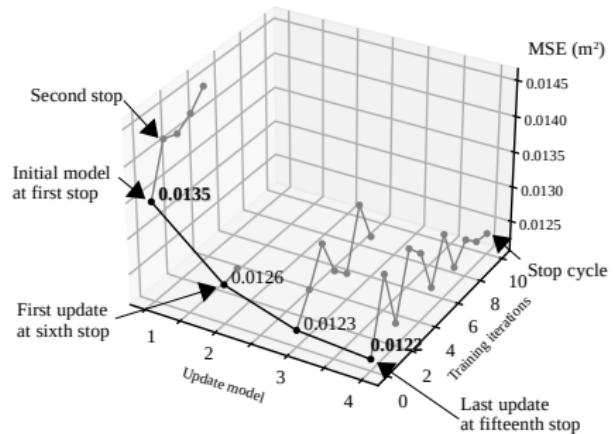
Model architecture



Boosting TinyML Performance with Hybrid Floating-Point 6-bit

Multi-Phase Model Optimization

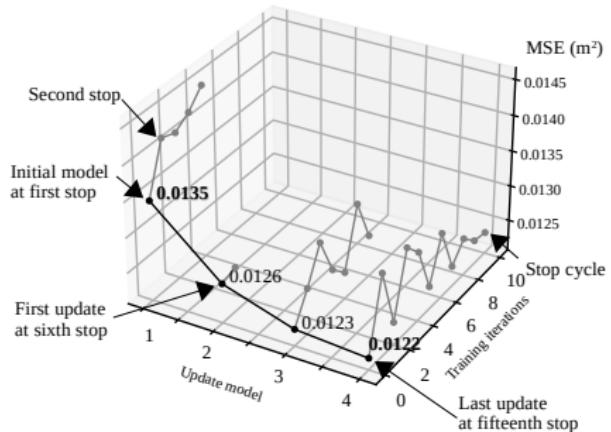
Training with iterative early stop
with Adam resets



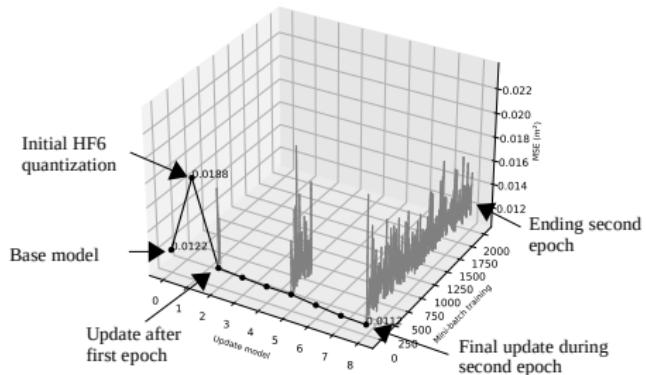
Boosting TinyML Performance with Hybrid Floating-Point 6-bit

Multi-Phase Model Optimization

Training with iterative early stop
with Adam resets

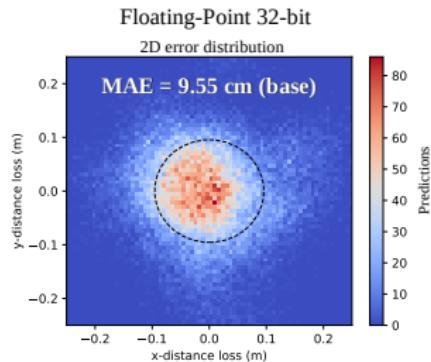


Quantization-aware training for
hybrid floating-point 6-bit



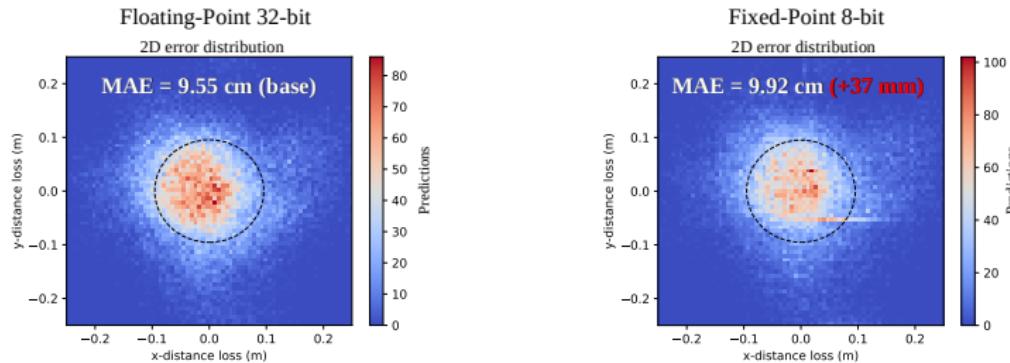
Boosting TinyML Performance with Hybrid Floating-Point 6-bit

Assessing X and Y Coordinate Prediction Accuracy Across Multiple Quantization Strategies



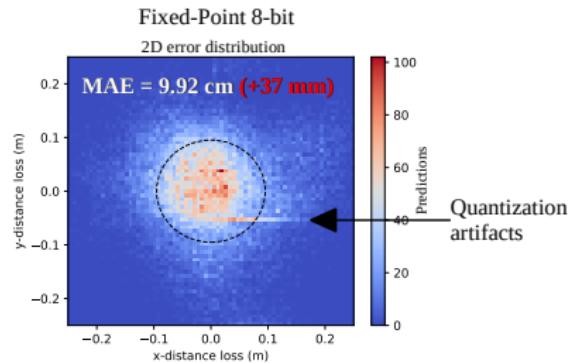
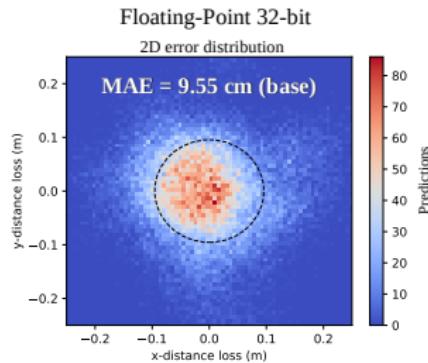
Boosting TinyML Performance with Hybrid Floating-Point 6-bit

Assessing X and Y Coordinate Prediction Accuracy Across Multiple Quantization Strategies



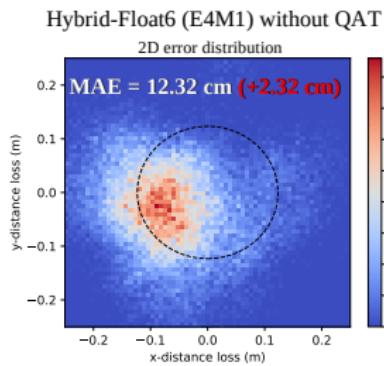
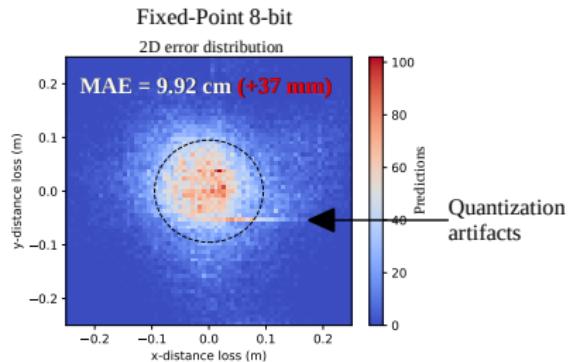
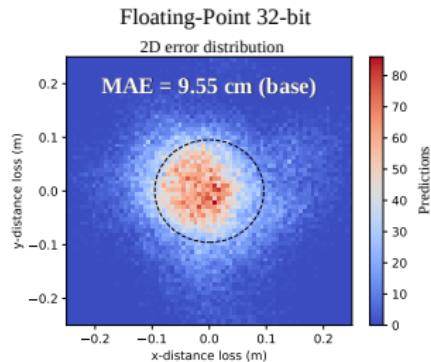
Boosting TinyML Performance with Hybrid Floating-Point 6-bit

Assessing X and Y Coordinate Prediction Accuracy Across Multiple Quantization Strategies



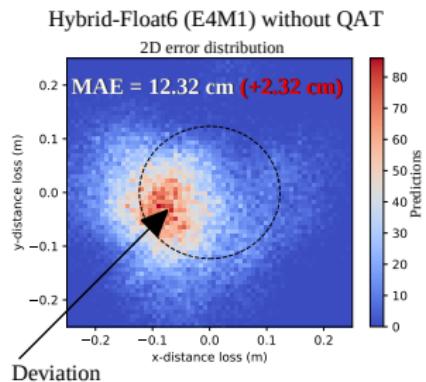
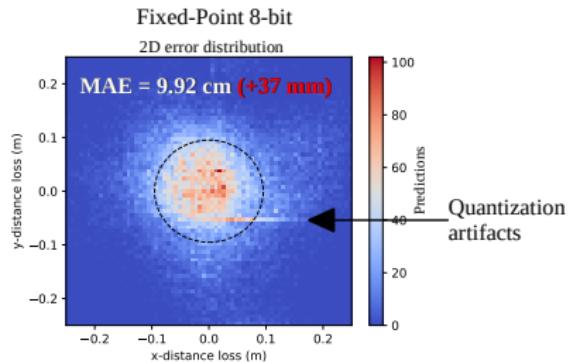
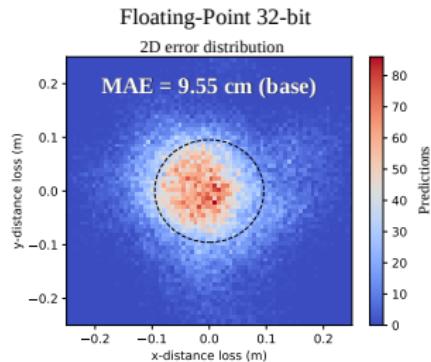
Boosting TinyML Performance with Hybrid Floating-Point 6-bit

Assessing X and Y Coordinate Prediction Accuracy Across Multiple Quantization Strategies



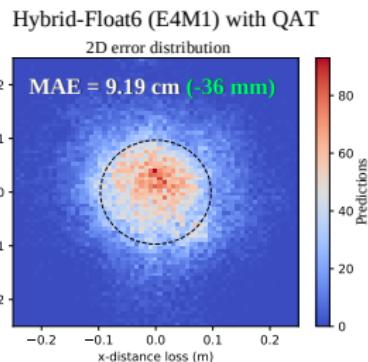
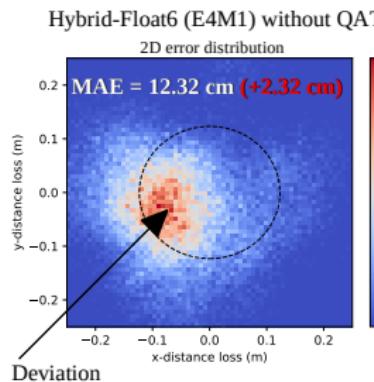
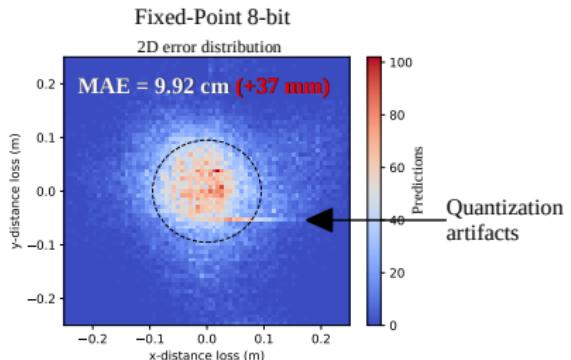
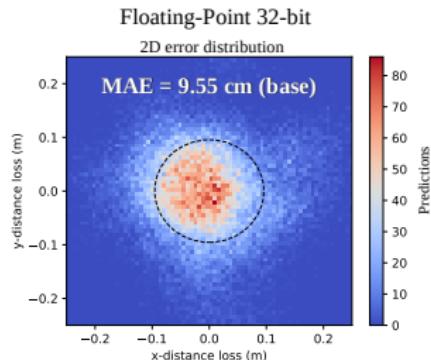
Boosting TinyML Performance with Hybrid Floating-Point 6-bit

Assessing X and Y Coordinate Prediction Accuracy Across Multiple Quantization Strategies



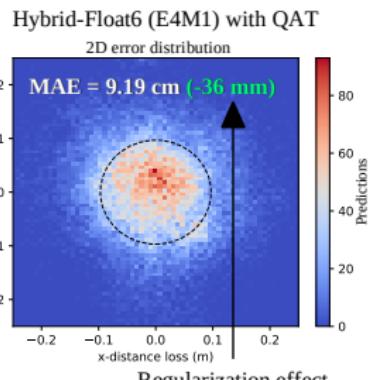
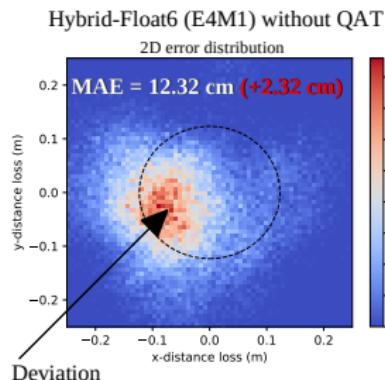
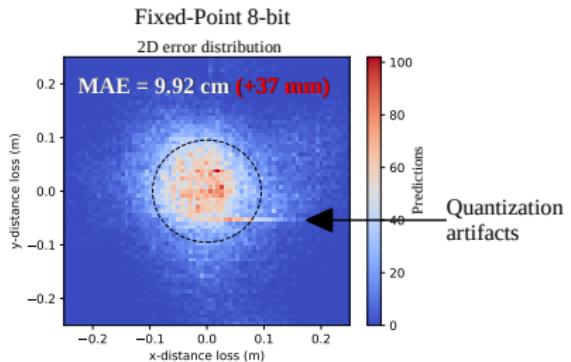
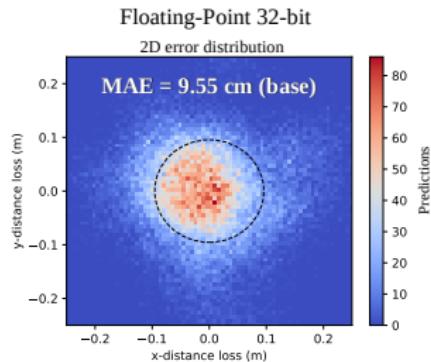
Boosting TinyML Performance with Hybrid Floating-Point 6-bit

Assessing X and Y Coordinate Prediction Accuracy Across Multiple Quantization Strategies



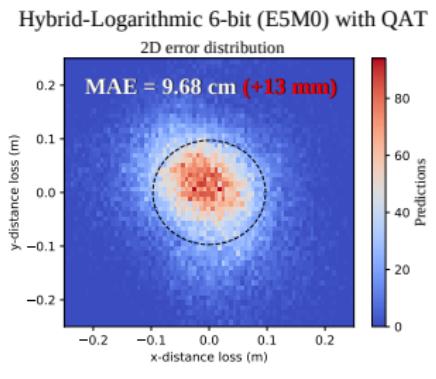
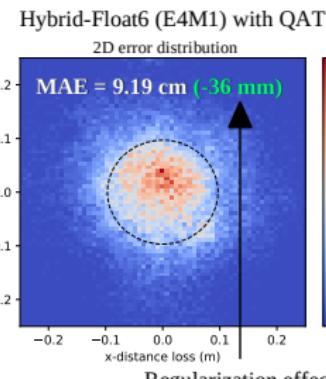
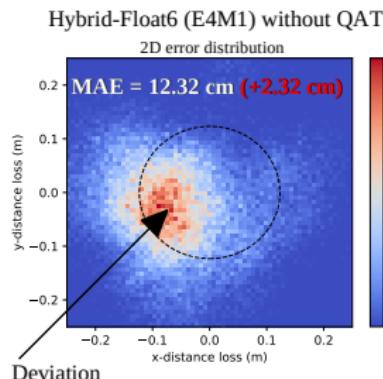
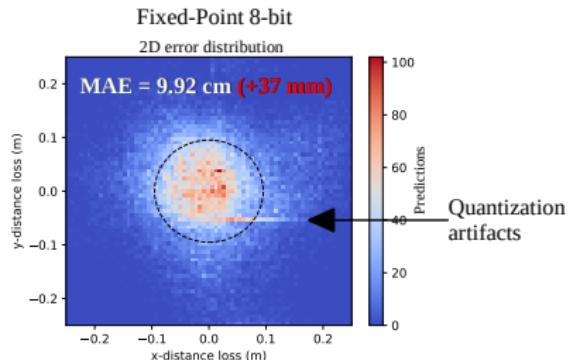
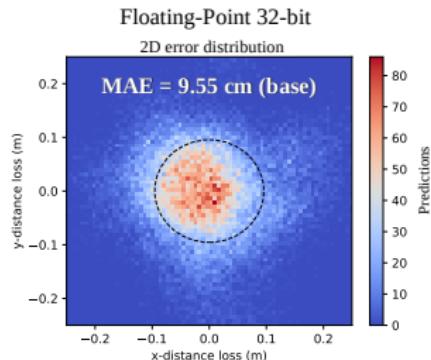
Boosting TinyML Performance with Hybrid Floating-Point 6-bit

Assessing X and Y Coordinate Prediction Accuracy Across Multiple Quantization Strategies



Boosting TinyML Performance with Hybrid Floating-Point 6-bit

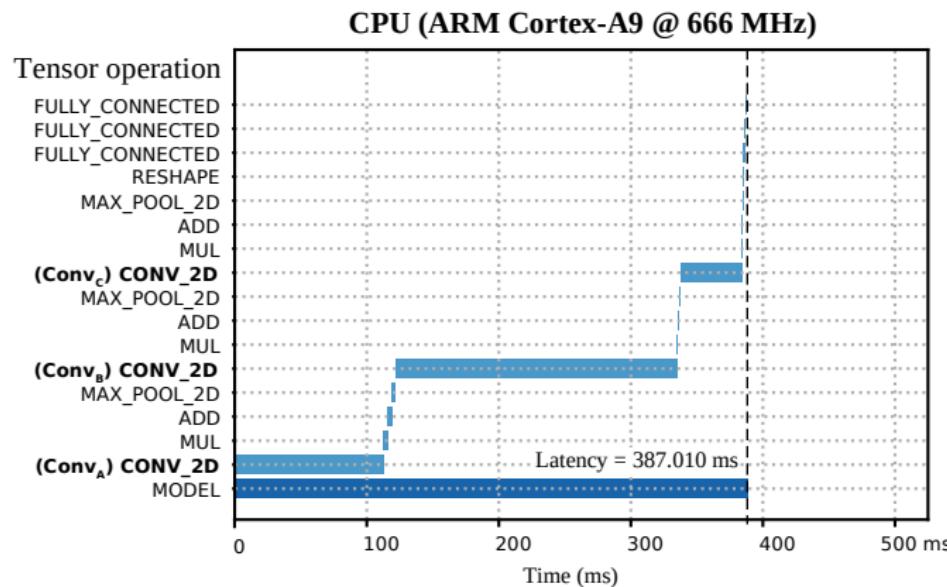
Assessing X and Y Coordinate Prediction Accuracy Across Multiple Quantization Strategies



Boosting TinyML Performance with Hybrid Floating-Point 6-bit

Runtime Profiling: Latencies and Scheduling on Floating-Point and Hybrid Float 6 Accelerators

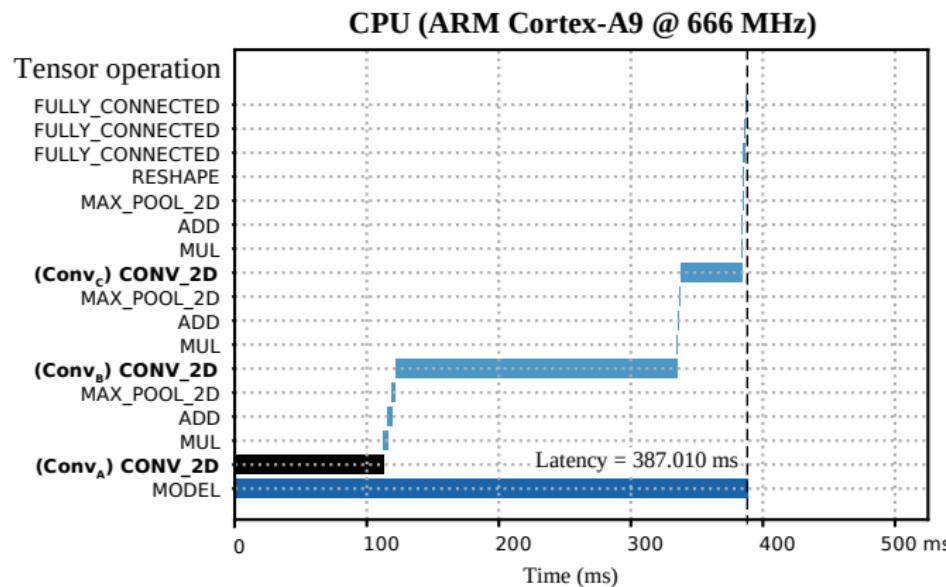
Tensor Op	CPU (ms)	TP FP32 (ms)	Gain	TP HF6 (ms)	Gain
Conv _A					
Conv _B					
Conv _C					



Boosting TinyML Performance with Hybrid Floating-Point 6-bit

Runtime Profiling: Latencies and Scheduling on Floating-Point and Hybrid Float 6 Accelerators

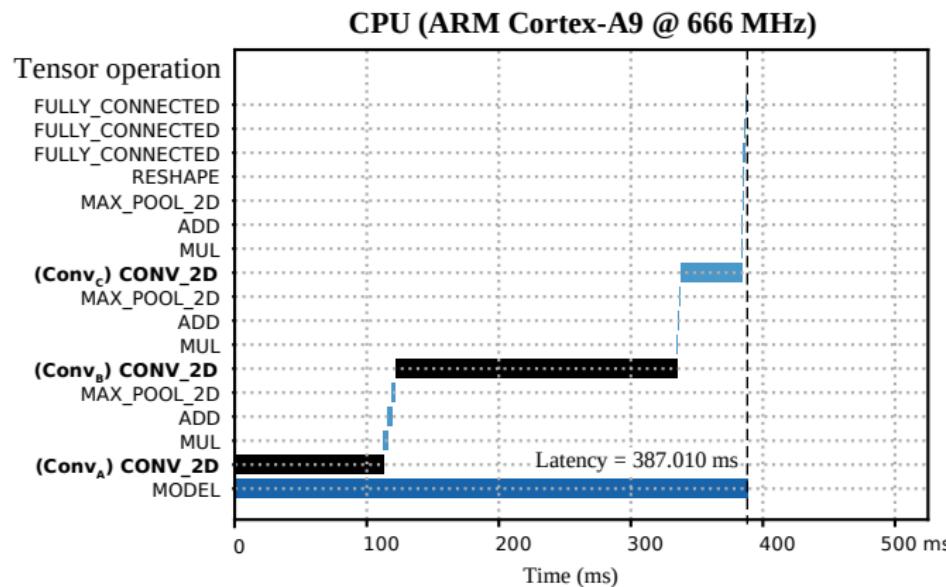
Tensor Op	CPU (ms)	TP FP32 (ms)	Gain	TP HF6 (ms)	Gain
Conv _A	112.24				
Conv _B					
Conv _C					



Boosting TinyML Performance with Hybrid Floating-Point 6-bit

Runtime Profiling: Latencies and Scheduling on Floating-Point and Hybrid Float 6 Accelerators

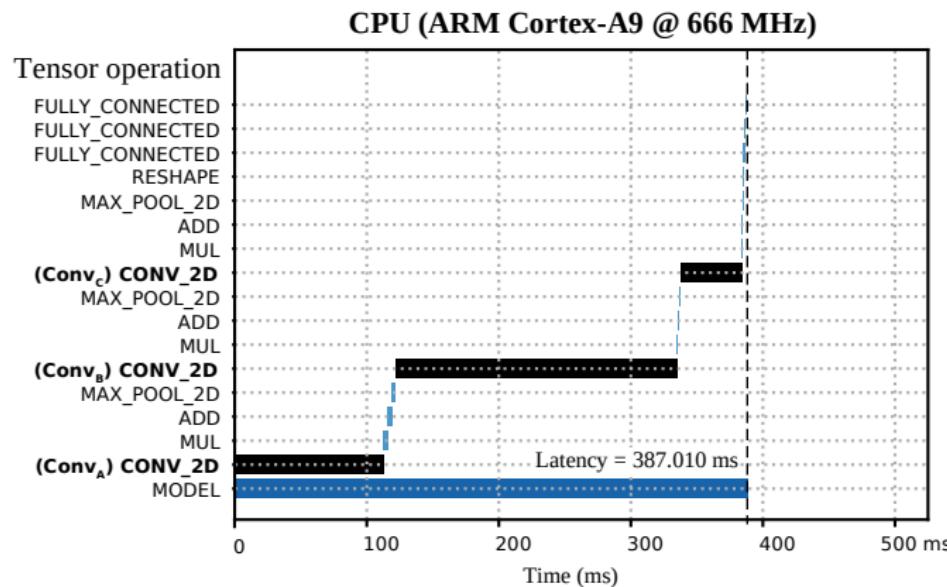
Tensor Op	CPU (ms)	TP FP32 (ms)	Gain	TP HF6 (ms)	Gain
Conv _A	112.24				
Conv _B	213.13				
Conv _C					



Boosting TinyML Performance with Hybrid Floating-Point 6-bit

Runtime Profiling: Latencies and Scheduling on Floating-Point and Hybrid Float 6 Accelerators

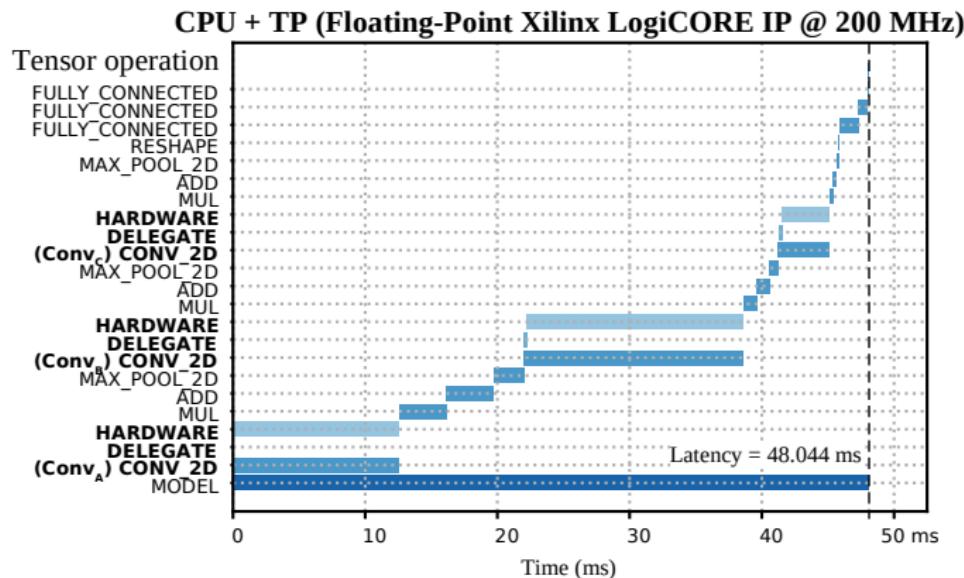
Tensor Op	CPU (ms)	TP FP32 (ms)	Gain	TP HF6 (ms)	Gain
Conv _A	112.24				
Conv _B	213.13				
Conv _C	46.59				



Boosting TinyML Performance with Hybrid Floating-Point 6-bit

Runtime Profiling: Latencies and Scheduling on Floating-Point and Hybrid Float 6 Accelerators

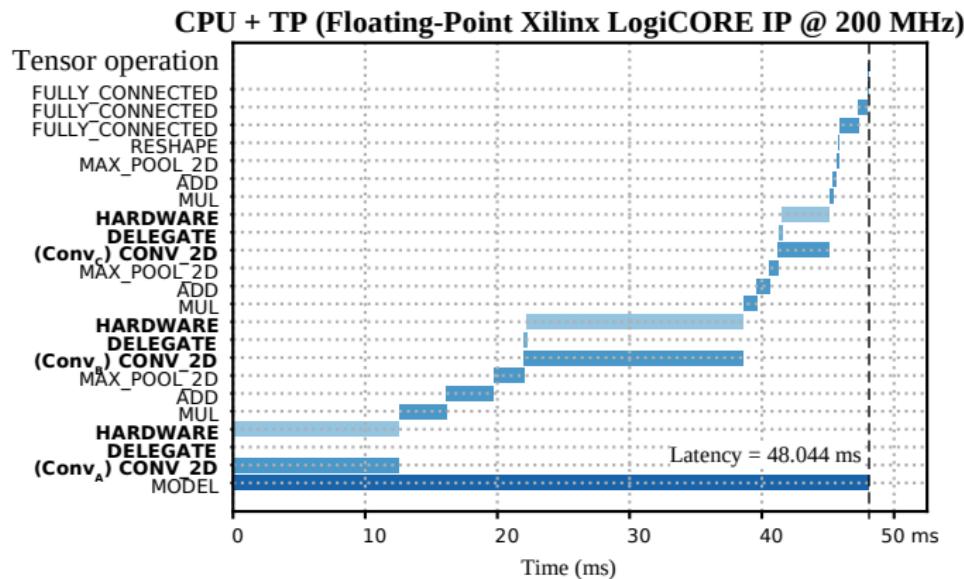
Tensor Op	CPU (ms)	TP FP32 (ms)	Gain	TP HF6 (ms)	Gain
Conv _A	112.24				
Conv _B	213.13				
Conv _C	46.59				



Boosting TinyML Performance with Hybrid Floating-Point 6-bit

Runtime Profiling: Latencies and Scheduling on Floating-Point and Hybrid Float 6 Accelerators

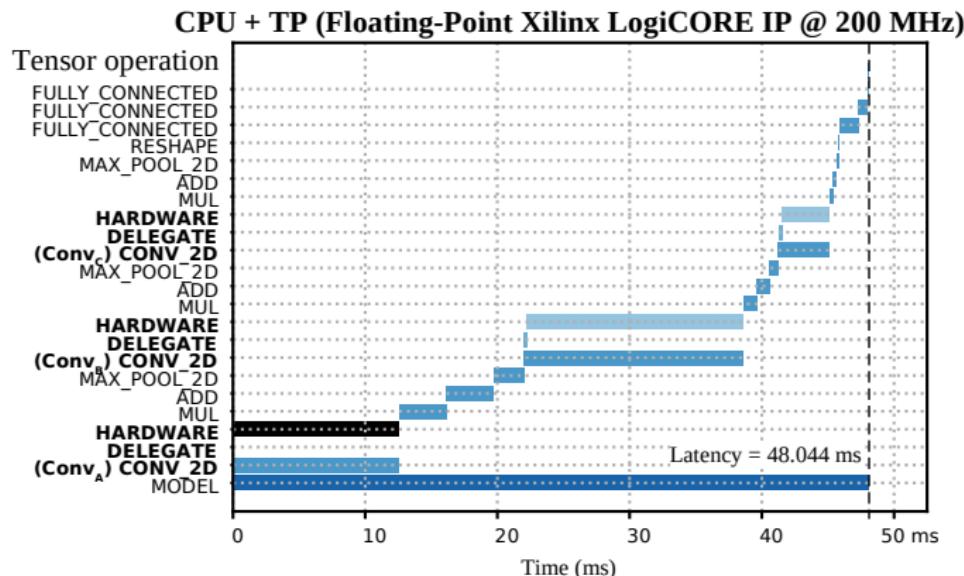
Tensor Op	CPU (ms)	TP FP32 (ms)	Gain	TP HF6 (ms)	Gain
Conv _A	112.24				
Conv _B	213.13				
Conv _C	46.59				



Boosting TinyML Performance with Hybrid Floating-Point 6-bit

Runtime Profiling: Latencies and Scheduling on Floating-Point and Hybrid Float 6 Accelerators

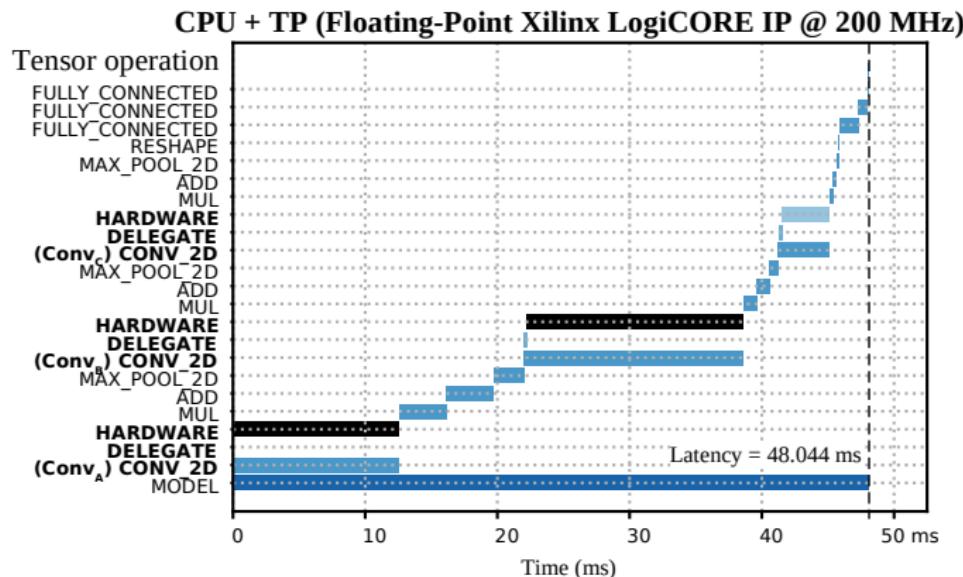
Tensor Op	CPU (ms)	TP FP32 (ms)	Gain	TP HF6 (ms)	Gain
Conv _A	112.24	12.49	8.9		
Conv _B	213.13				
Conv _C	46.59				



Boosting TinyML Performance with Hybrid Floating-Point 6-bit

Runtime Profiling: Latencies and Scheduling on Floating-Point and Hybrid Float 6 Accelerators

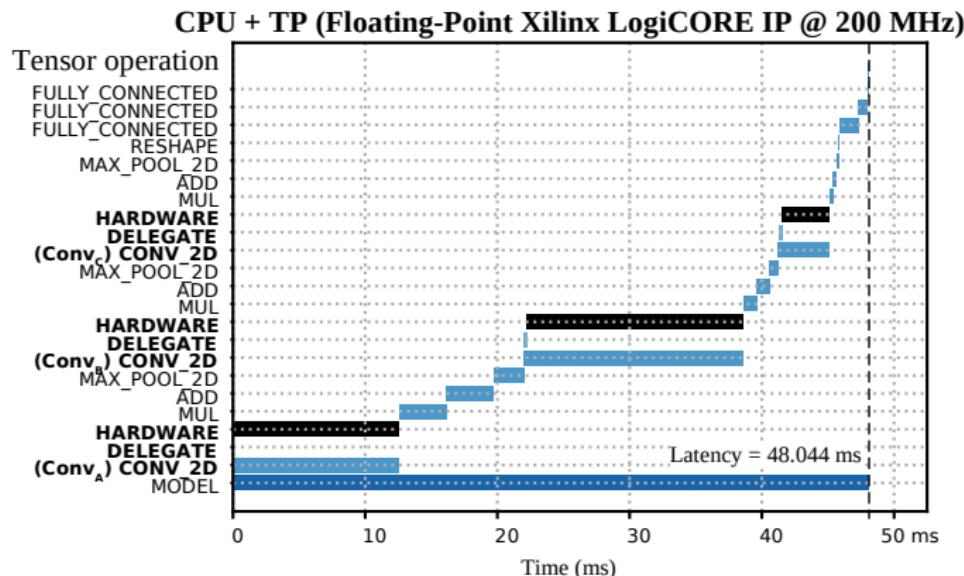
Tensor Op	CPU (ms)	TP FP32 (ms)	Gain	TP HF6 (ms)	Gain
Conv _A	112.24	12.49	8.9		
Conv _B	213.13	16.39	13.0		
Conv _C	46.59				



Boosting TinyML Performance with Hybrid Floating-Point 6-bit

Runtime Profiling: Latencies and Scheduling on Floating-Point and Hybrid Float 6 Accelerators

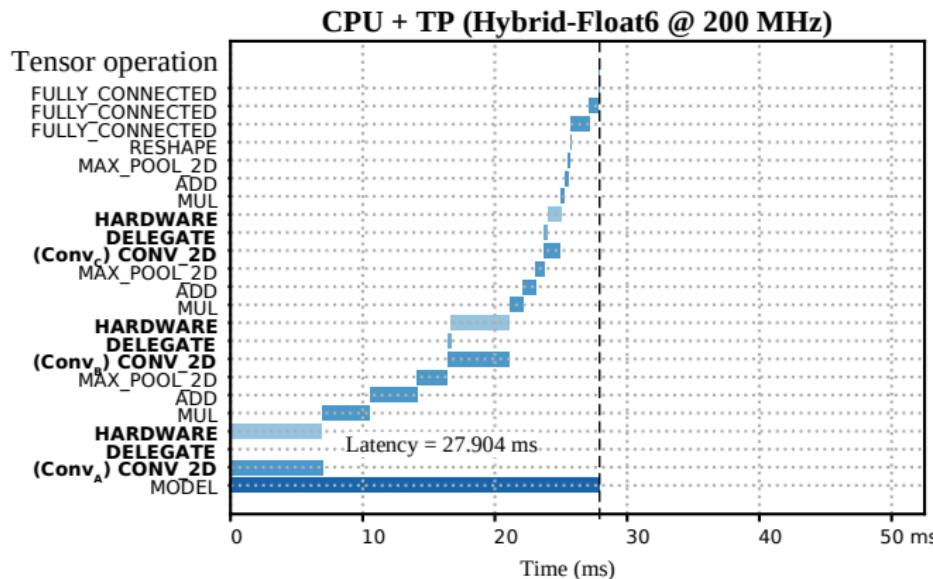
Tensor Op	CPU (ms)	TP FP32 (ms)	Gain	TP HF6 (ms)	Gain
Conv _A	112.24	12.49	8.9		
Conv _B	213.13	16.39	13.0		
Conv _C	46.59	3.59	12.9		



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Runtime Profiling: Latencies and Scheduling on Floating-Point and Hybrid Float 6 Accelerators

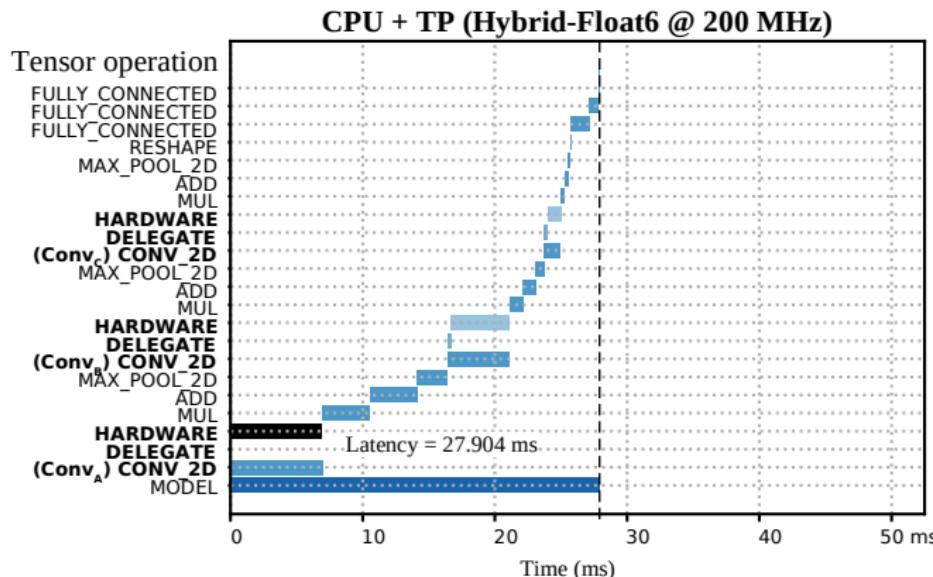
Tensor Op	CPU (ms)	TP FP32 (ms)	Gain	TP HF6 (ms)	Gain
Conv _A	112.24	12.49	8.9		
Conv _B	213.13	16.39	13.0		
Conv _C	46.59	3.59	12.9		



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Runtime Profiling: Latencies and Scheduling on Floating-Point and Hybrid Float 6 Accelerators

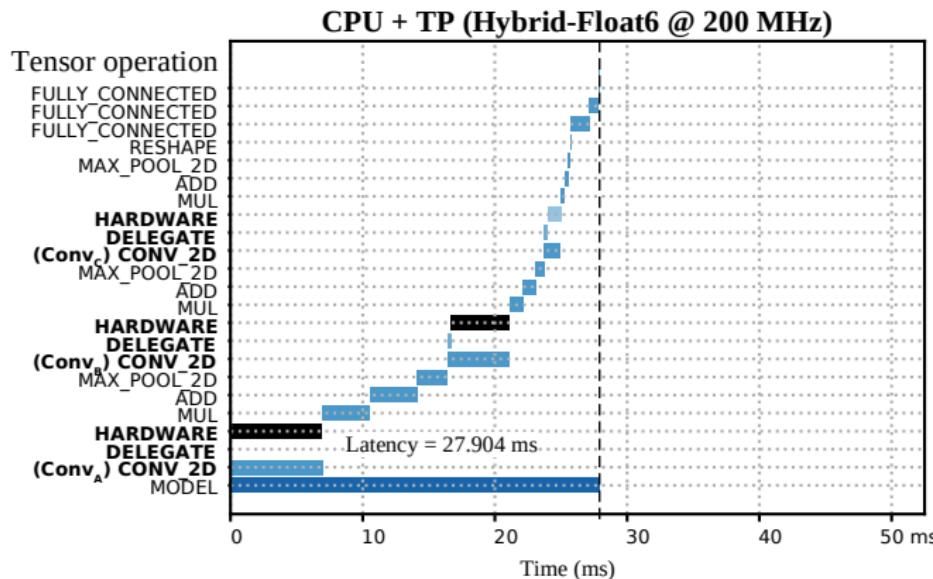
Tensor Op	CPU (ms)	TP FP32 (ms)	Gain	TP HF6 (ms)	Gain
Conv _A	112.24	12.49	8.9	6.92	16.2
Conv _B	213.13	16.39	13.0		
Conv _C	46.59	3.59	12.9		



Boosting TinyML Performance with Hybrid Floating-Point 6-bit

Runtime Profiling: Latencies and Scheduling on Floating-Point and Hybrid Float 6 Accelerators

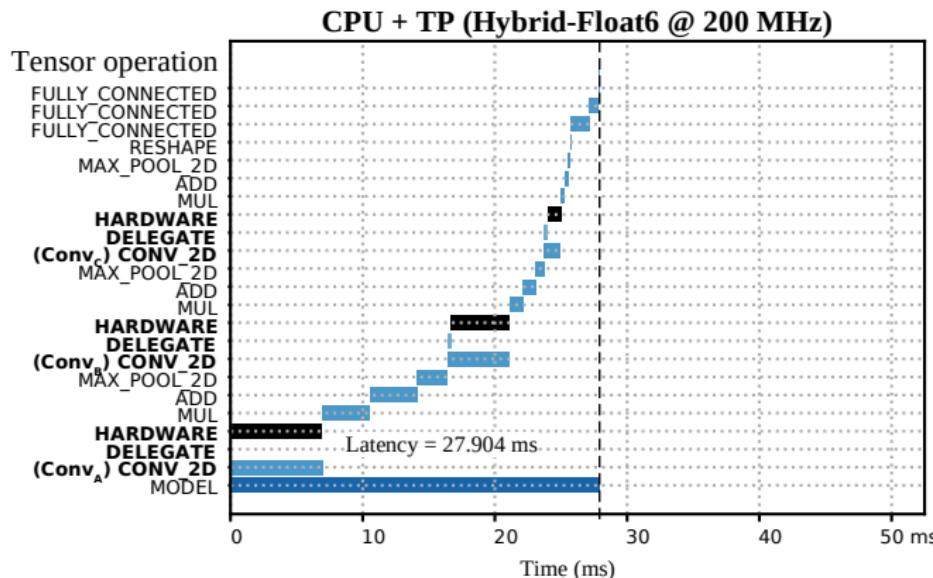
Tensor Op	CPU (ms)	TP FP32 (ms)	Gain	TP HF6 (ms)	Gain
Conv _A	112.24	12.49	8.9	6.92	16.2
Conv _B	213.13	16.39	13.0	4.41	48.3
Conv _C	46.59	3.59	12.9		



Boosting TinyML Performance with Hybrid Floating-Point 6-bit

Runtime Profiling: Latencies and Scheduling on Floating-Point and Hybrid Float 6 Accelerators

Tensor Op	CPU (ms)	TP FP32 (ms)	Gain	TP HF6 (ms)	Gain
Conv _A	112.24	12.49	8.9	6.92	16.2
Conv _B	213.13	16.39	13.0	4.41	48.3
Conv _C	46.59	3.59	12.9	0.99	47.0

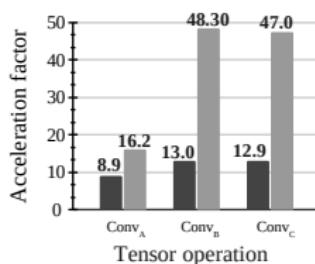


Boosting TinyML Performance with Hybrid Floating-Point 6-bit

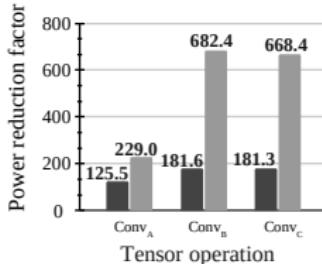
Final Benchmarking Insights: Accelerators vs. CPU in Performance and Power Efficiency

Floating-Point Hybrid-Float6

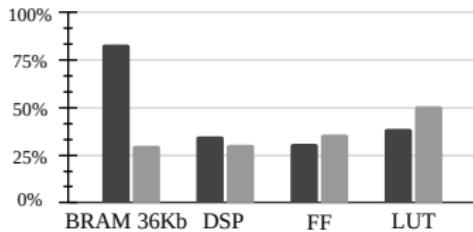
Acceleration vs. CPU



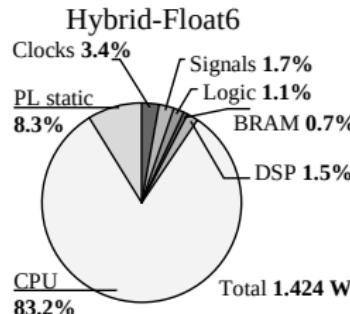
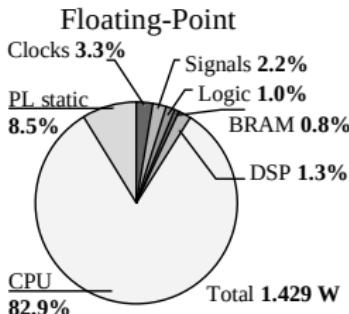
Power reduction vs. CPU



Hardware resource utilization.



Estimated power dissipation on the Zynq-7007S AP SoC with PS at 666 MHz and PL at 200 MHz



1 Methodology

2 Custom Floating-Point MAC Designs and Quantization Techniques

3 Case Studies

4 Conclusions

Conclusion and Future Research

- **HW/SW Design Methodology for Low-Power Neural Network Acceleration with Hybrid Custom Floating-Point Arithmetic**
- **Technological Transformation**

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- On-device iterative optimization with non-negativity constraints using 4-bit weights

- **Technological Transformation**

- Inference was the beginning in TinyML. Low-precision floating-point is opening the door for a new generation of on-device training accelerators that are essential in the next phase of AI evolution.

Publications

Journal Articles

- **Yarib Nevarez**, David Rotermund, Klaus R Pawelzik, and Alberto Garcia-Ortiz, "Accelerating Spike-by-Spike Neural Networks on FPGA With Hybrid Custom Floating-Point and Logarithmic Dot-Product Approximation," *IEEE Access*, vol. 9, pp. 80603–80620, May 2021, doi: [10.1109/ACCESS.2021.3085216](https://doi.org/10.1109/ACCESS.2021.3085216).
- **Yarib Nevarez**, Andreas Beering, Amir Najafi, Ardalan Najafi, Wanli Yu, Yizhi Chen, Karl-Ludwig Krieger, and Alberto Garcia-Ortiz, "CNN Sensor Analytics With Hybrid-Float6 Quantization on Low-Power Embedded FPGAs," *IEEE Access*, vol. 11, pp. 4852–4868, January 2023, doi: [10.1109/ACCESS.2023.3235866](https://doi.org/10.1109/ACCESS.2023.3235866).

Conference Proceedings

- **Yarib Nevarez**, Alberto Garcia-Ortiz, David Rotermund, and Klaus R Pawelzik, "Accelerator framework of spike-by-spike neural networks for inference and incremental learning in embedded systems," 2020 9th International Conference on Modern Circuits and Systems Technologies (MOCAST), Bremen, 2020, pp. 1–5, doi: [10.1109/MOCAST49295.2020.9200288](https://doi.org/10.1109/MOCAST49295.2020.9200288).
- Wanli Yu, Ardalan Najafi, **Yarib Nevarez**, Yanqiu Huang and Alberto Garcia-Ortiz, "TAAC: Task Allocation Meets Approximate Computing for Internet of Things," 2020 IEEE International Symposium on Circuits and Systems (ISCAS), Sevilla, 2020, pp. 1-5, doi: [10.1109/ISCAS45731.2020.9180895](https://doi.org/10.1109/ISCAS45731.2020.9180895).

Publications

- Amir Najafi, Ardalan Najafi, **Yarib Nevarez** and Alberto Garcia-Ortiz, "Learning-Based On-Chip Parallel Interconnect Delay Estimation," 2022 11th International Conference on Modern Circuits and Systems Technologies (MOCAST), Bremen, 2022, pp. 1–5, doi: 10.1109/MOCAST49295.2020.9200288.
- Yizhi Chen, **Yarib Nevarez**, Zhonghai Lu, and Alberto Garcia-Ortiz, "Accelerating Non-Negative Matrix Factorization on Embedded FPGA with Hybrid Logarithmic Dot-Product Approximation," 2022 IEEE 15th International Symposium on Embedded Multicore/Many-core Systems-on-Chip (MCSoC), Malaysia, 2022, pp. 239–246, doi: 10.1109/MCSoC57363.2022.00070.
- Ardalan Najafi, Wanli Yu, **Yarib Nevarez**, Amir Najafi, Andreas Beering, Karl-Ludwig Krieger, and Alberto Garcia-Ortiz, "Acoustic Emission Source Localization using Approximate Discrete Wavelet Transform," 2023 12th International Conference on Modern Circuits and Systems Technologies (MOCAST), Bremen, 2023, pp. 1–5, doi: 10.1109/MOCAST57943.2023.10176952.

Thank You for Your Attention