FZI Research Center for Information Technology

A PyTorch-Compatible Spike Encoding Framework for Energy-Efficient Neuromorphic Applications

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(2) Karlsruhe Institute of Technology, Karlsruhe, Germany
(3) NXP Semiconductors Germany GmbH, Munich, Germany

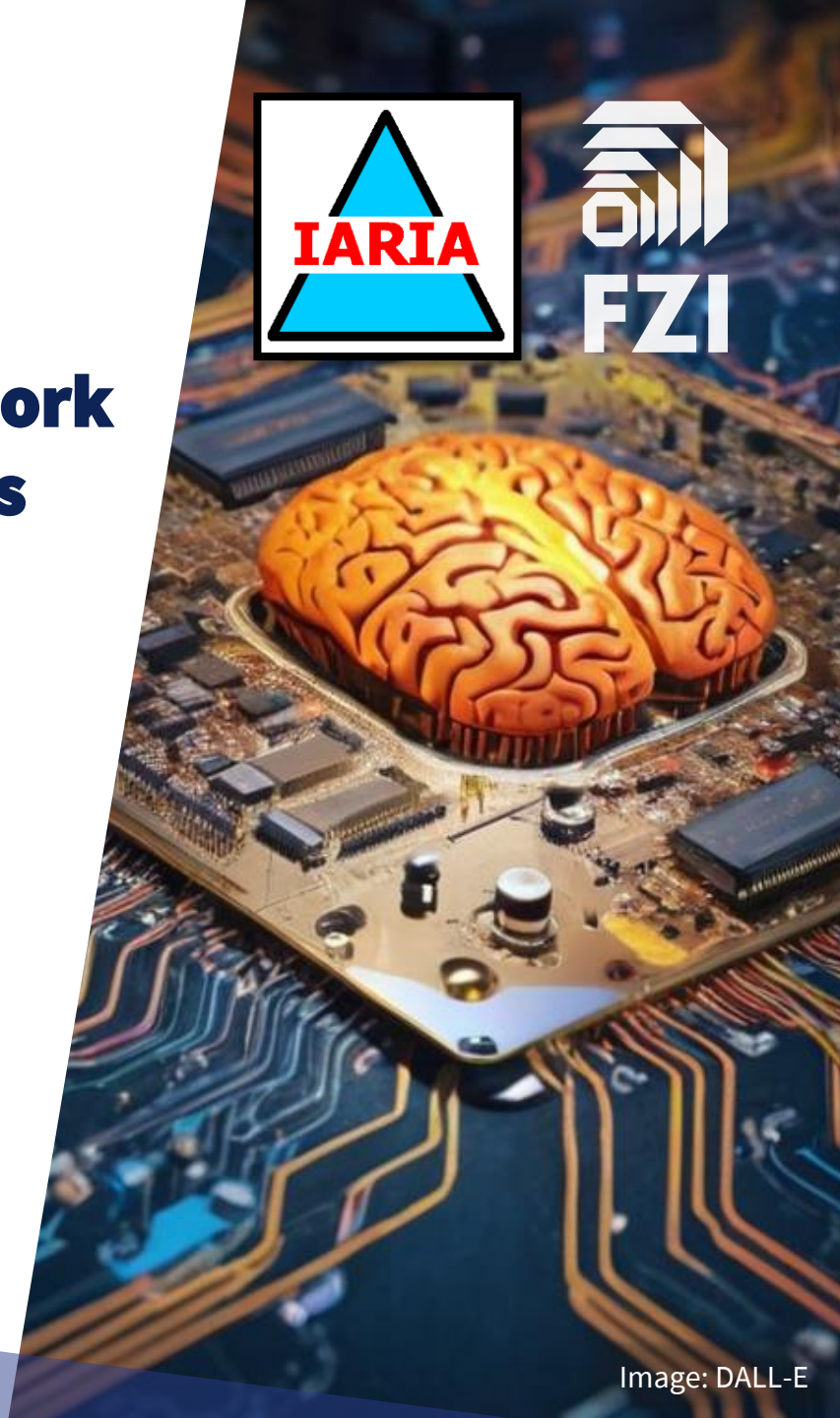

Image: DALL-E

16 May 2025

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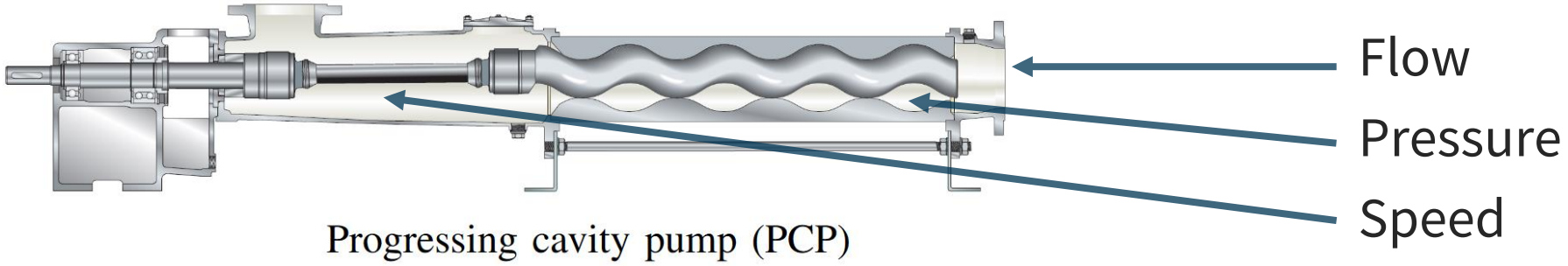
Alexandru Vasilache

Research Scientist - Forschungszentrum Informatik (FZI)

- Education:
  - B.Sc. & M.Sc. in Computer Science @ Karlsruhe Institute of Technology (KIT)
    - Specialization: AI & Robotics
  - Currently Ph.D. Student @ Karlsruhe Institute of Technology (KIT)
- Research Topics:
  - Neuromorphic Computing:
    - Spiking Neural Networks (SNNs)
    - Energy Efficiency in Embedded Neural Networks

Motivation

Spiking Neural Networks (SNNs) for Predictive Maintenance



Progressing cavity pump (PCP)

- Option 1:
  - Multiple Expensive Sensors

Image: Baoji

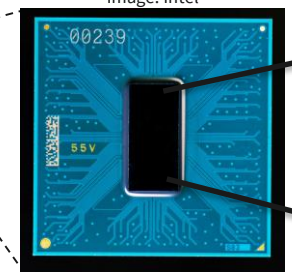
Image: nieruf

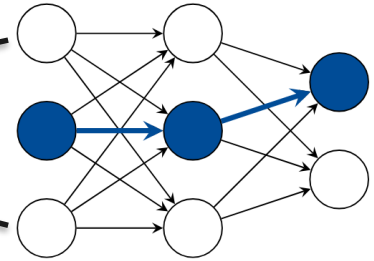
Image: Sensata-BEI

- Option 2:
  - Single Vibration Sensor
  - Embedded Spiking Neural Network (SNN)

Image: Siemens

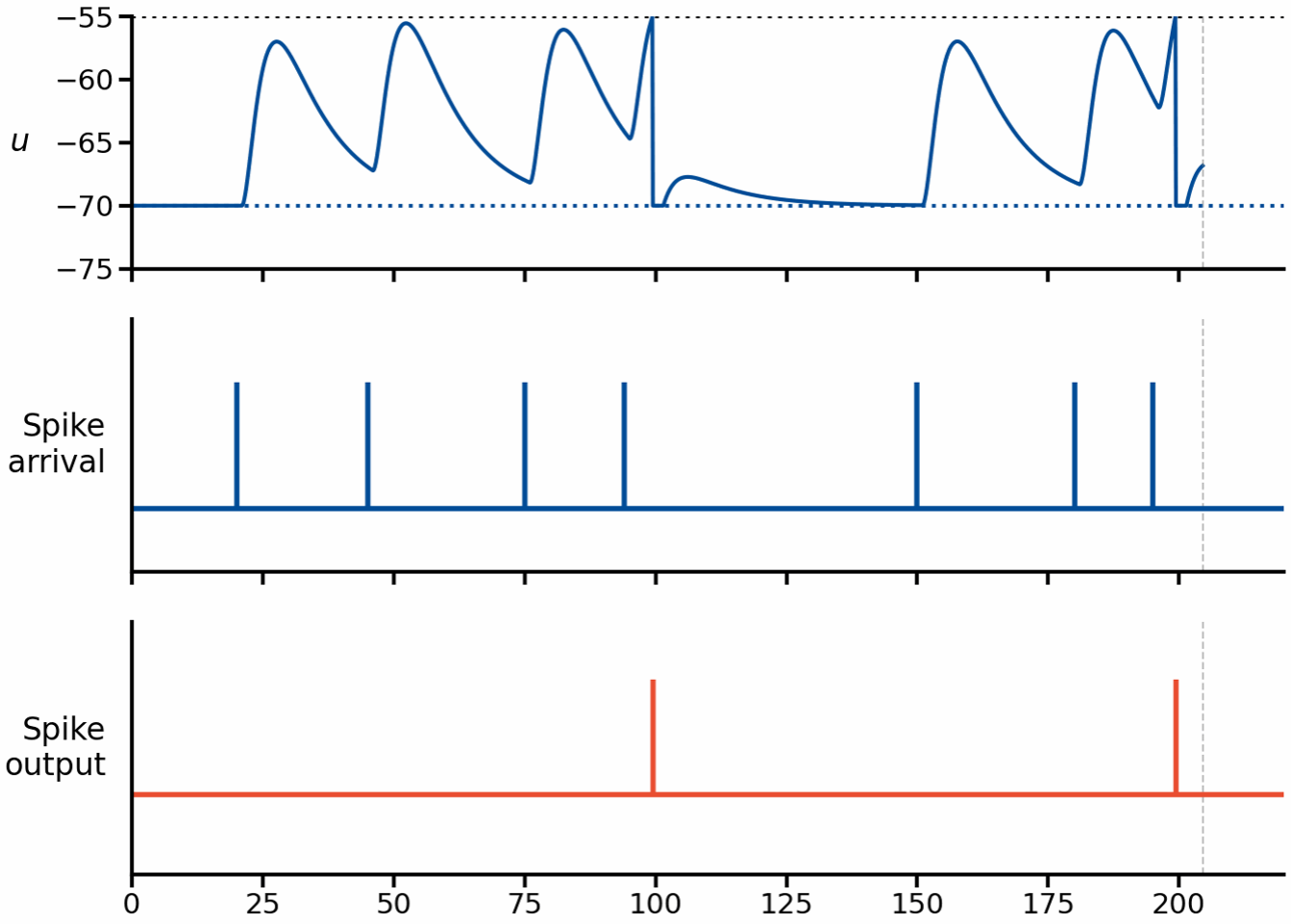
Image: Intel



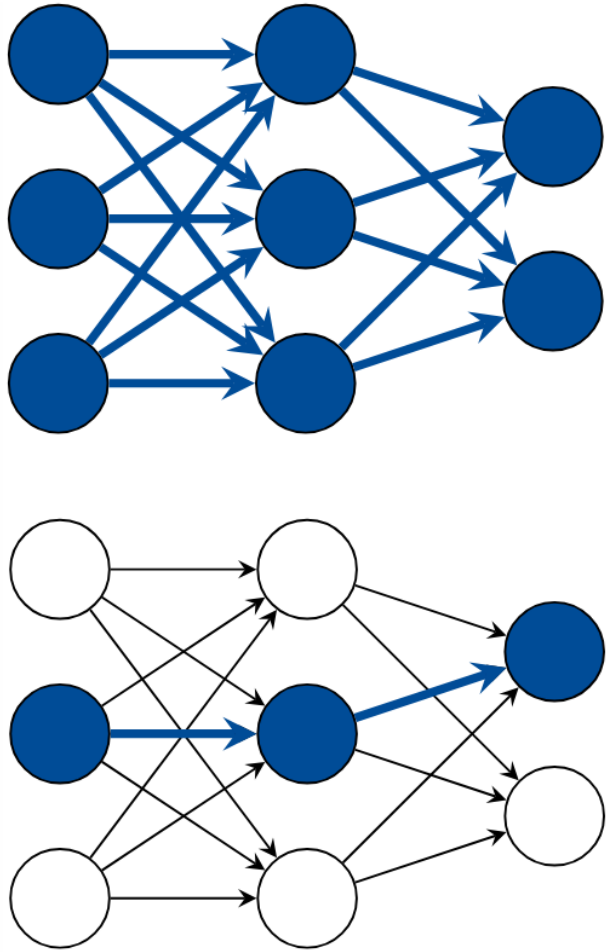


Spiking Neural Networks (SNNs)

Spiking Neurons



Sparsity

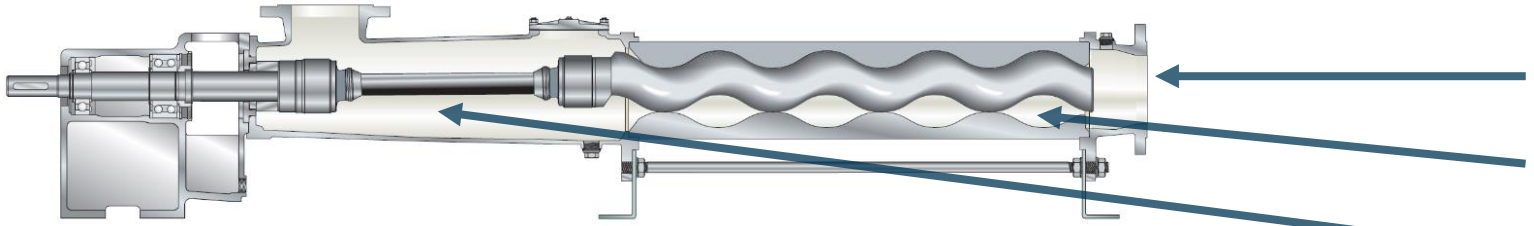


ANN

SNN

Motivation

Spiking Neural Networks (SNNs) for Predictive Maintenance



Progressing cavity pump (PCP)

Flow

Pressure

Speed

- Option 1:
  - Multiple Expensive Sensors

Image: Baoji

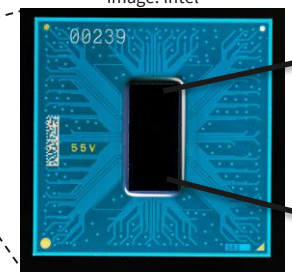
Image: nieruf

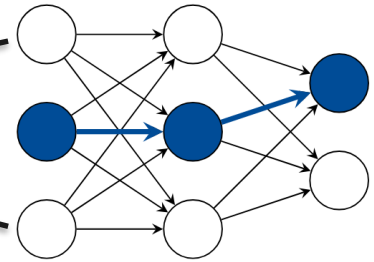
Image: Sensata-BEI

- Option 2:
  - Single Vibration Sensor – Numeric Values Spikes
  - Embedded Spiking Neural Network (SNN)

Image: Siemens

Image: Intel

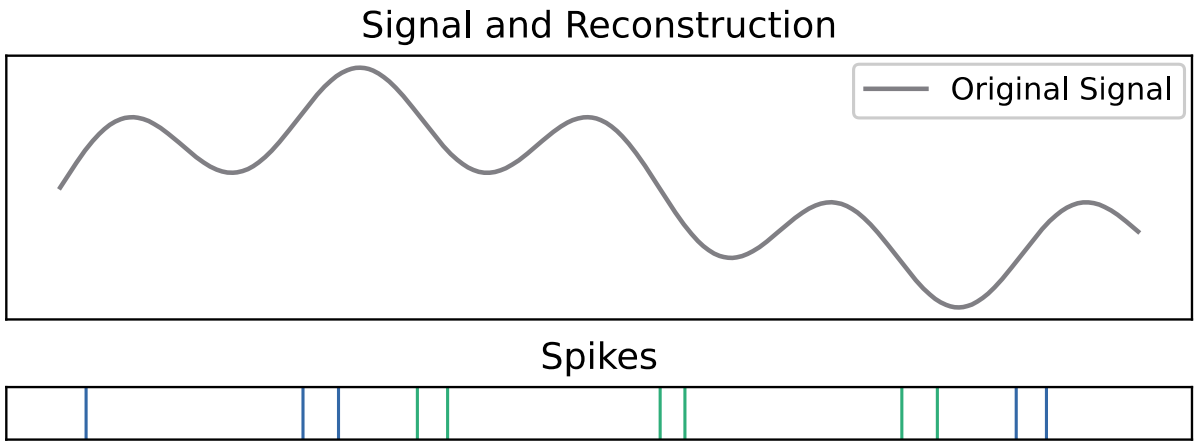




Spike Encoding

Encoding

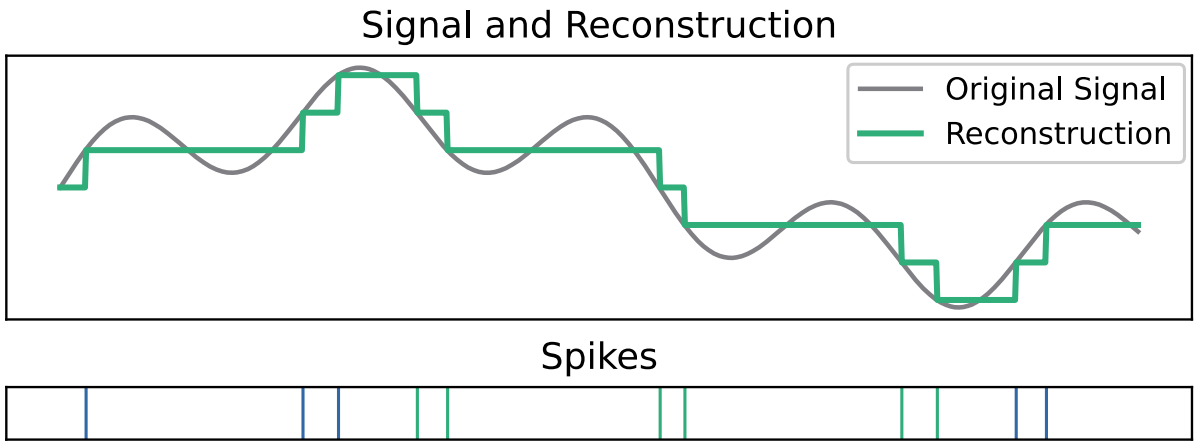
```
signal = tensor([0.0, 0.2, 0.4, 0.2, 0.0])

sf = StepForwardConverter(threshold=0.1)
spikes = sf.encode(signal)

# returns up/down spikes:
# up:   [0, 1, 1, 0, 0]
# down: [0, 0, 0, 0, 1]
```



Spike Encoding

Decoding

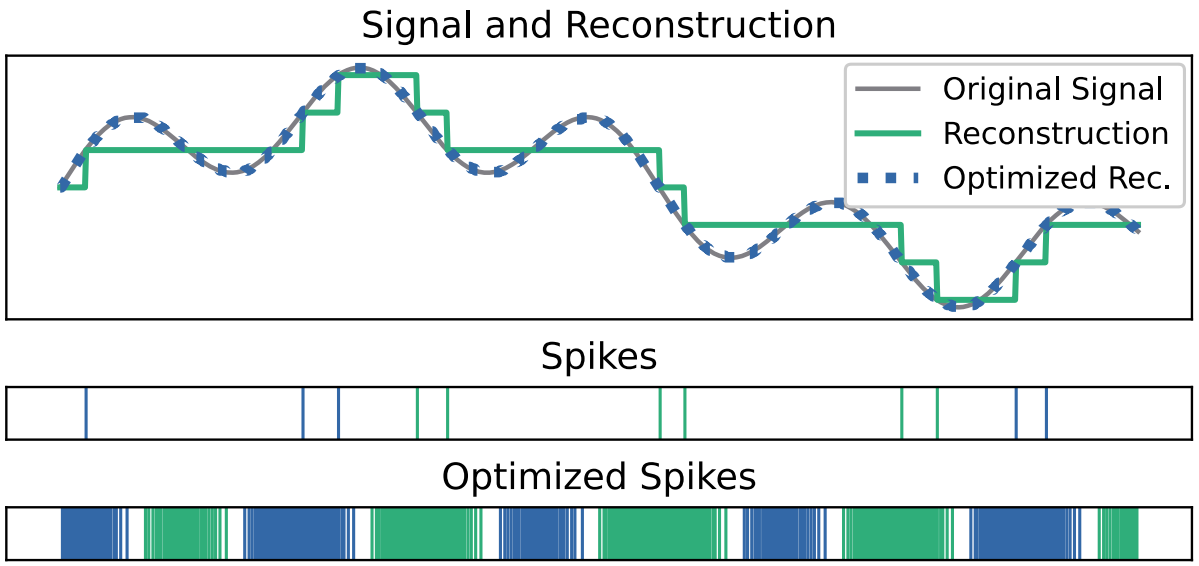
```
signal = tensor([0.0, 0.2, 0.4, 0.2, 0.0])

sf = StepForwardConverter(threshold=0.1)
spikes = sf.encode(signal)

sf.decode(spikes)
# returns [0.0, 0.1, 0.2, 0.2, 0.1]
```



Spike Encoding

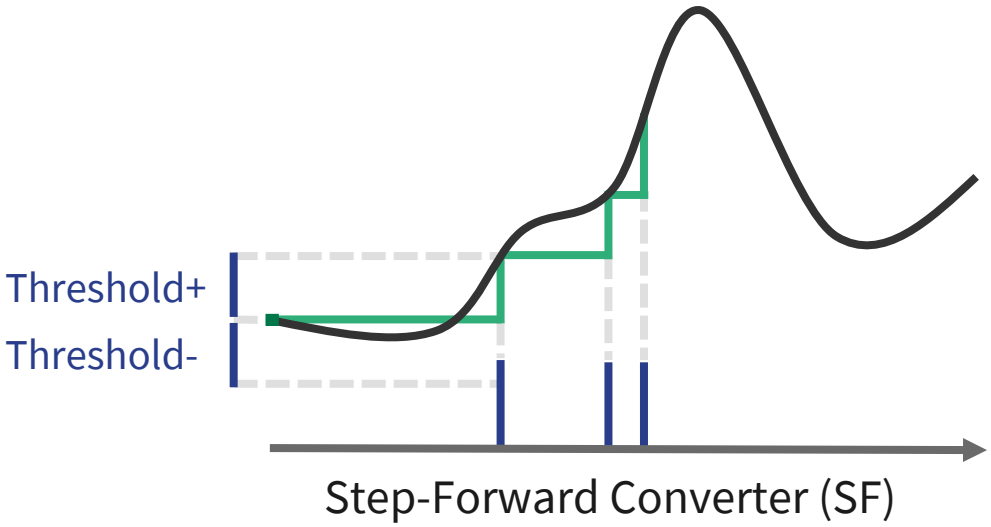
Optimization

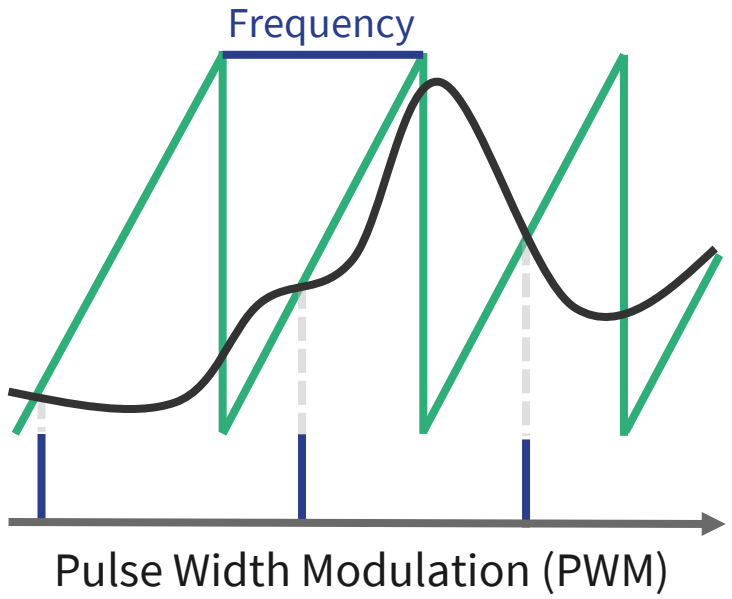
```
signal = tensor([0.0, 0.2, 0.4, 0.2, 0.0])

sf = StepForwardConverter(threshold=0.1)
spikes = sf.encode(signal)

sf.decode(spikes)

threshold = sf.optimize(signal)
```



Spike Encoding Algorithms

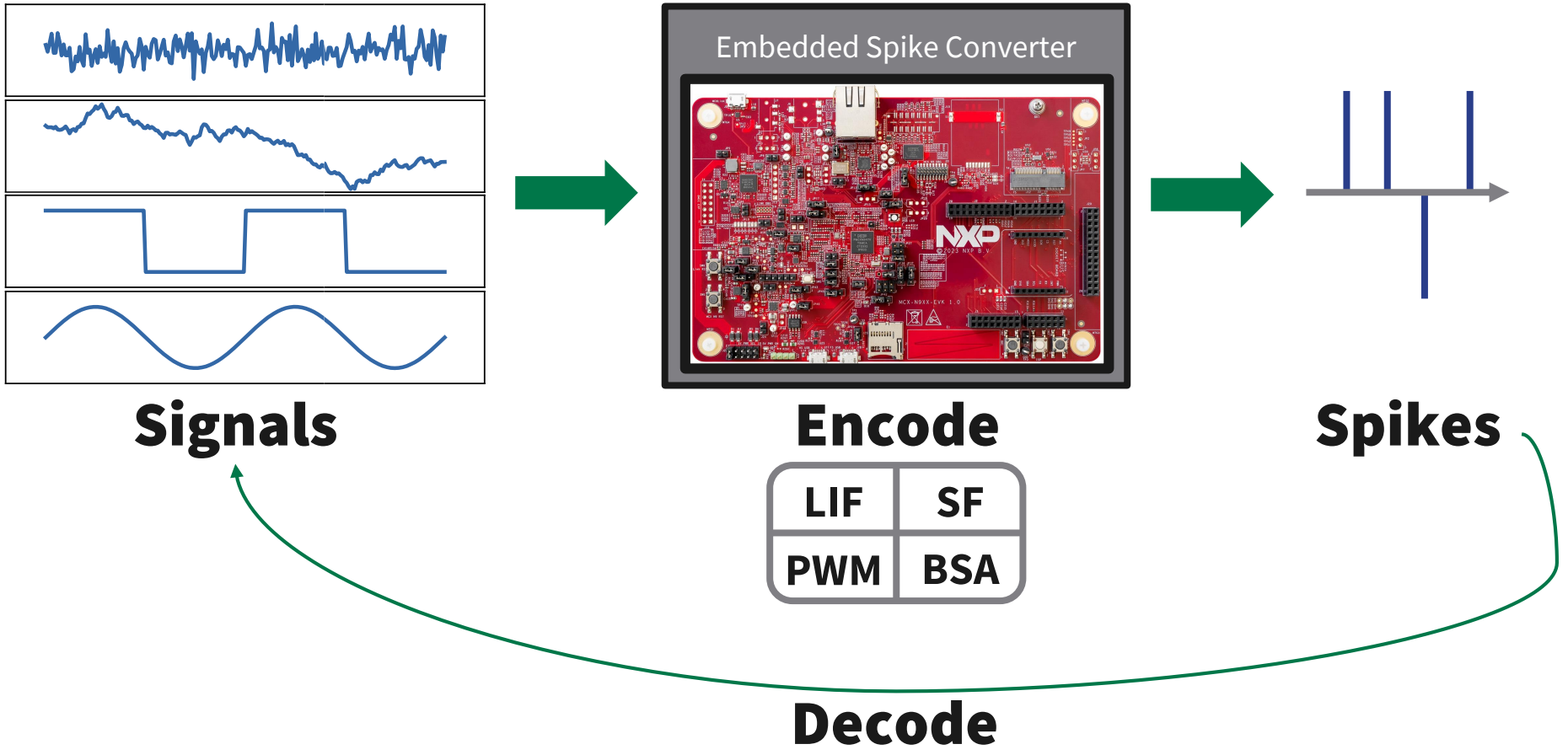
Step-Forward (SF) and Pulse Width Modulation (PWM)





Evaluation

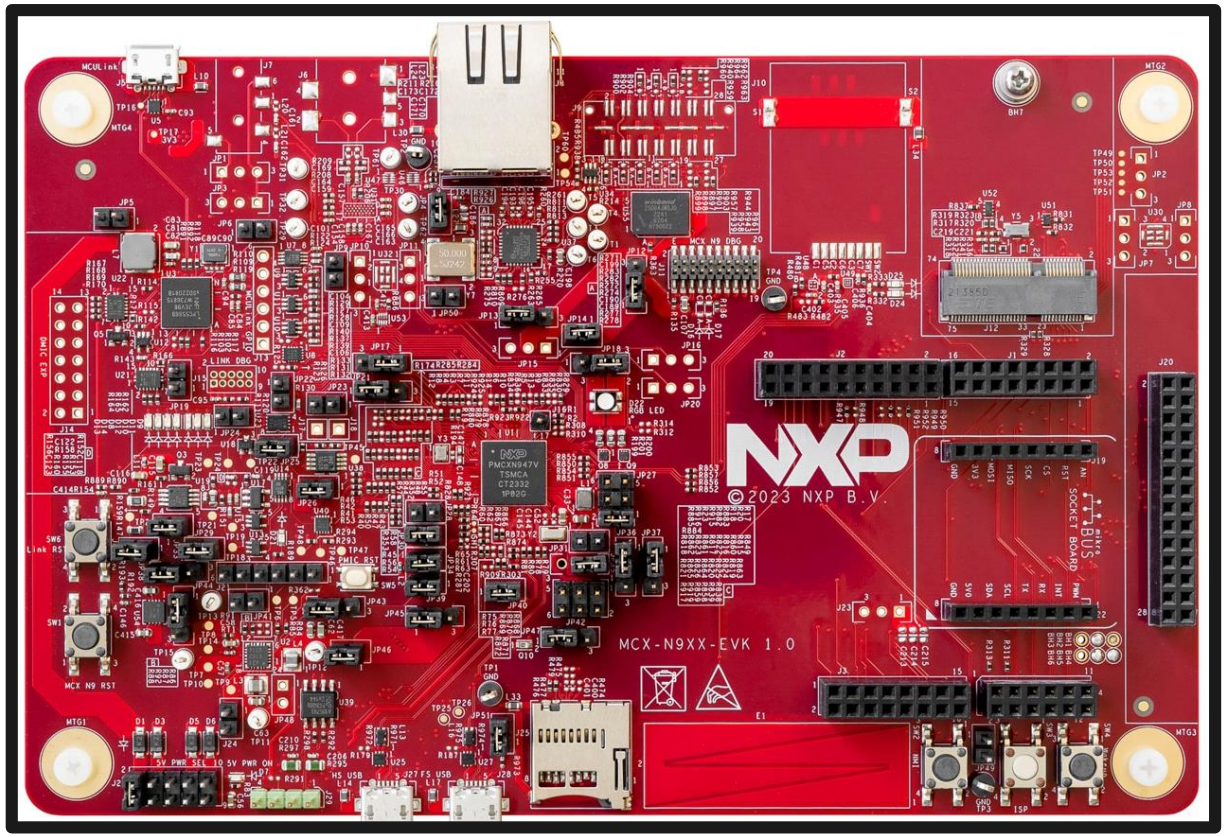
What is the best algorithm? Time Power Energy Sparsity Error



Embedded Platform

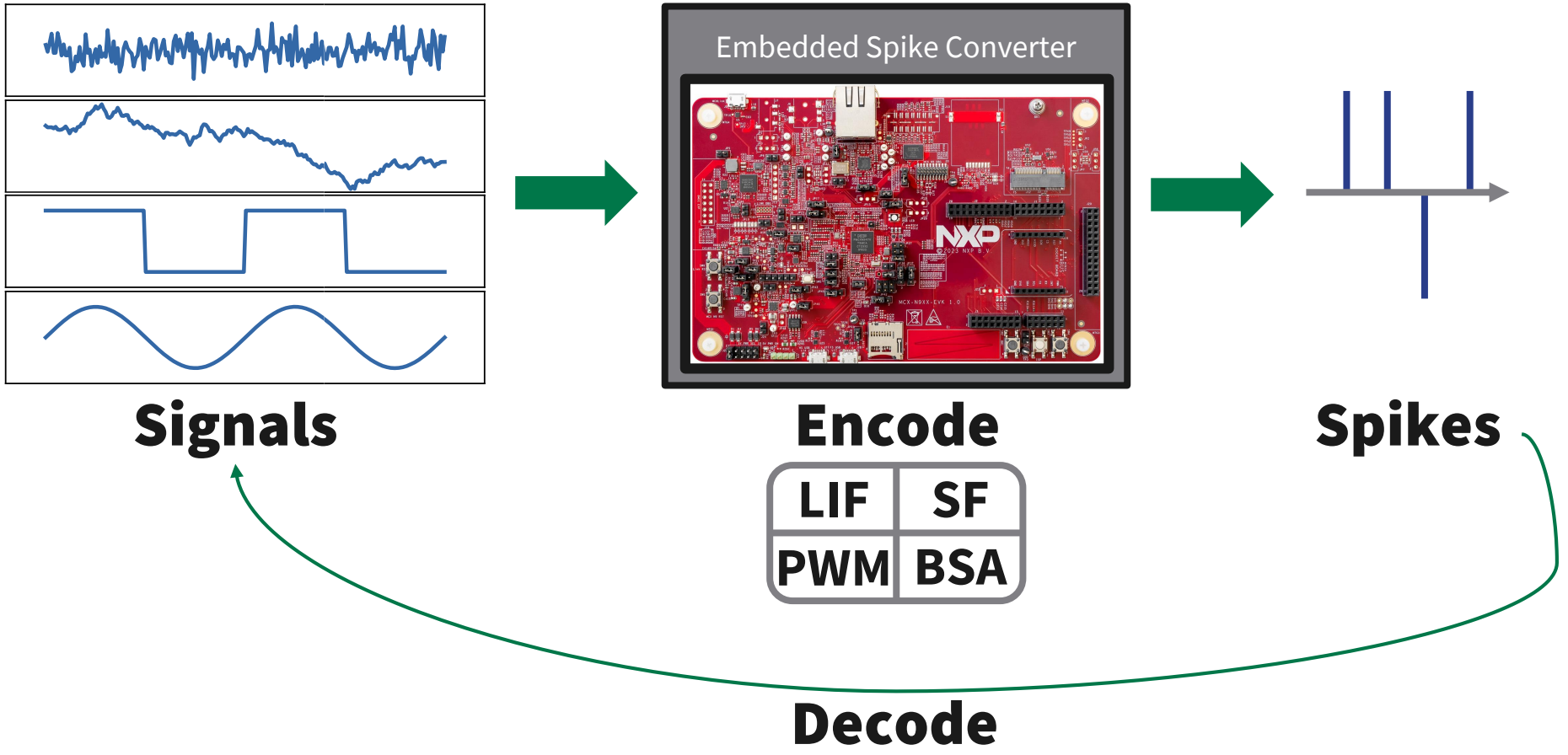
NXP MCX-N947

- Development board
- Efficient Power Measurement (on-board)
- On-board Debugger (MCU-Link)



Evaluation

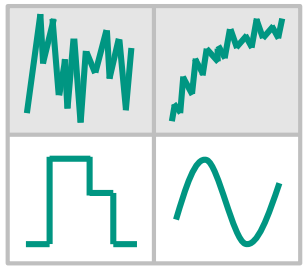
What is the best algorithm? Time Power Energy Sparsity Error

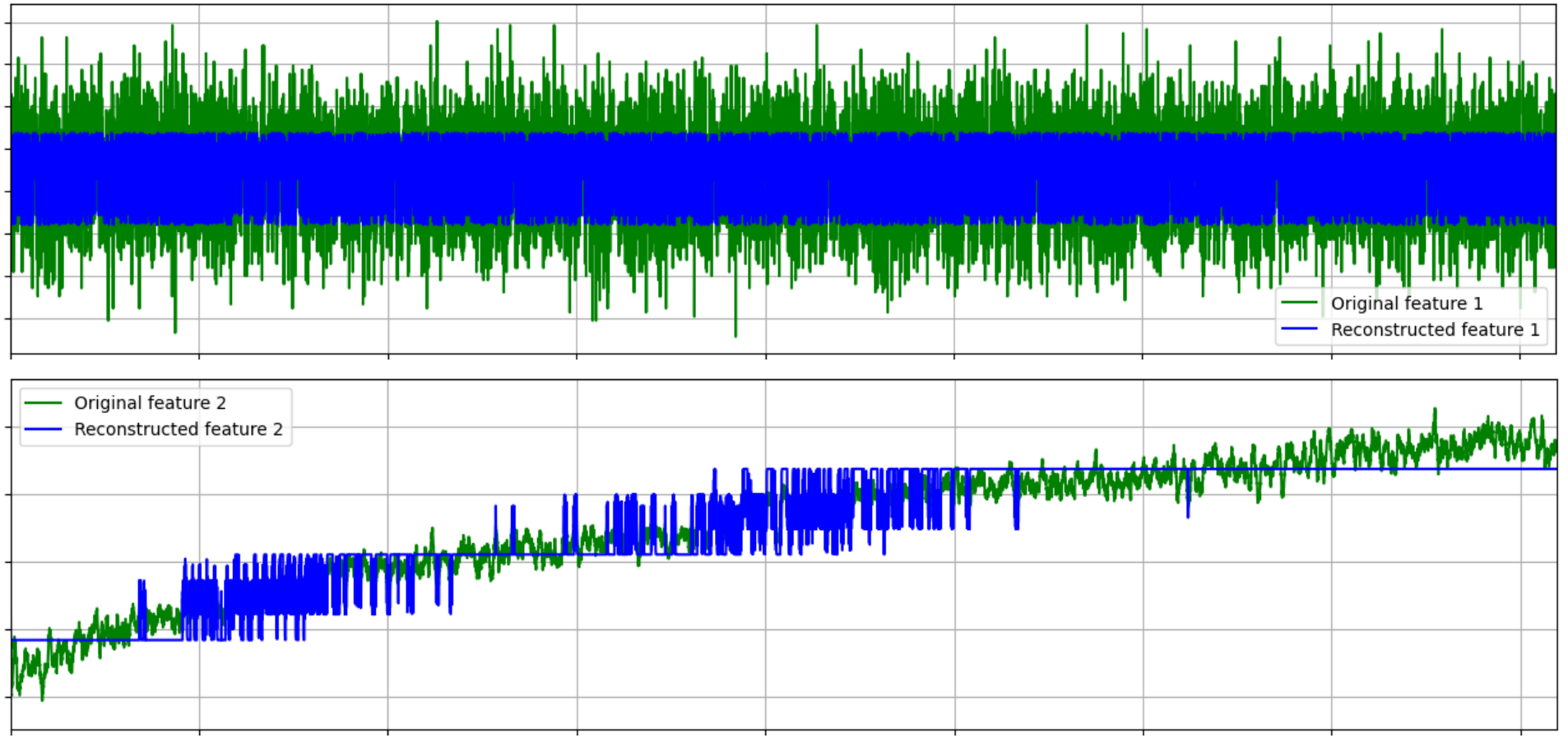


Evaluation: Leaky Integrate and Fire (LIF) Encoding

What is the best algorithm?

LIF	SF
PWM	BSA

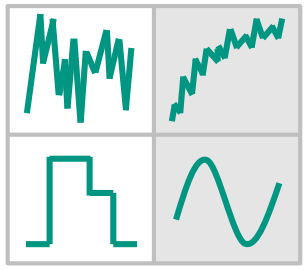


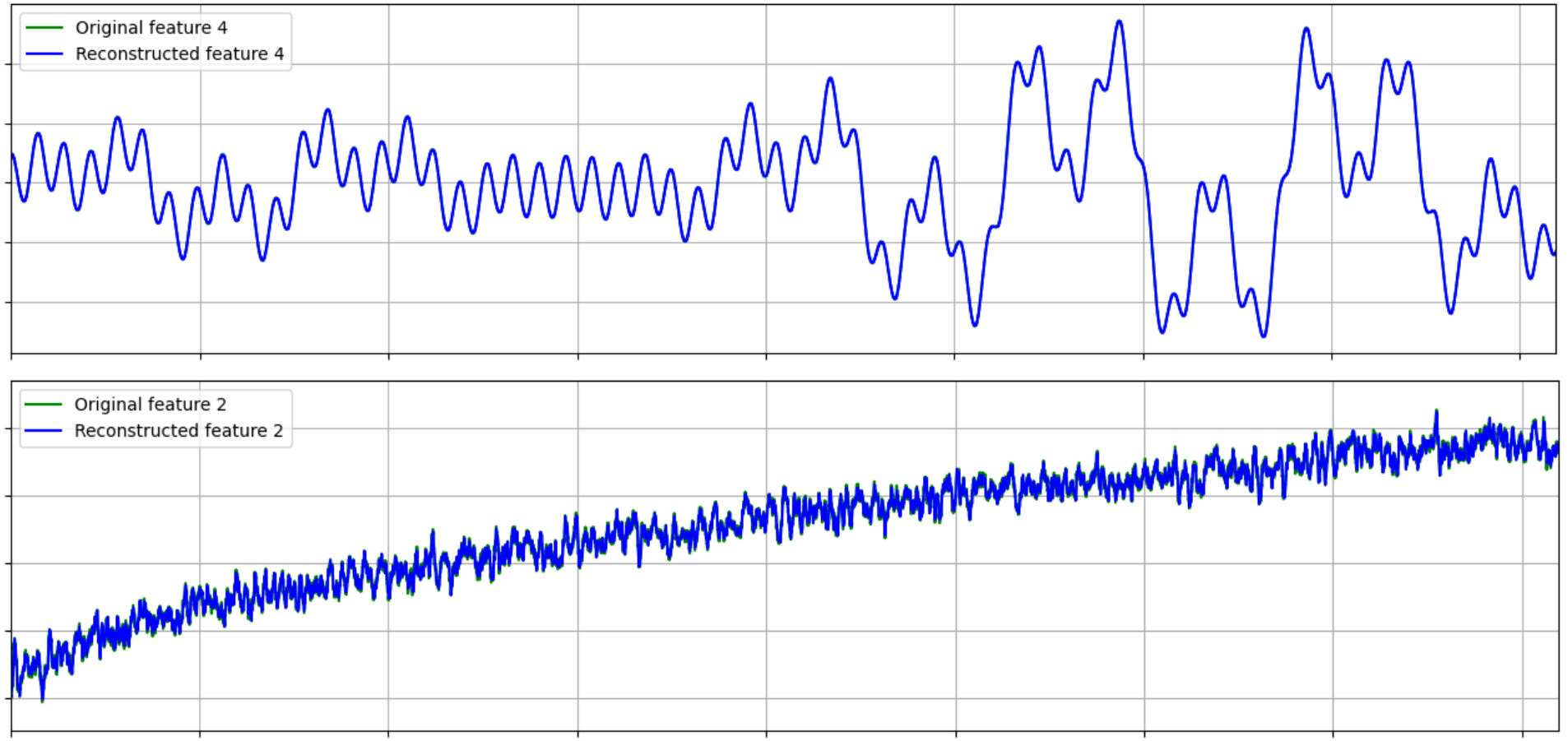


Evaluation: Step-forward encoding (SF)

What is the best algorithm?

LIF	SF
PWM	BSA

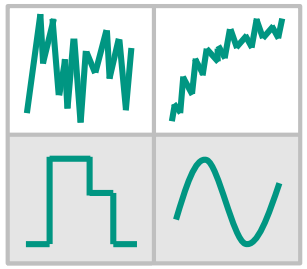


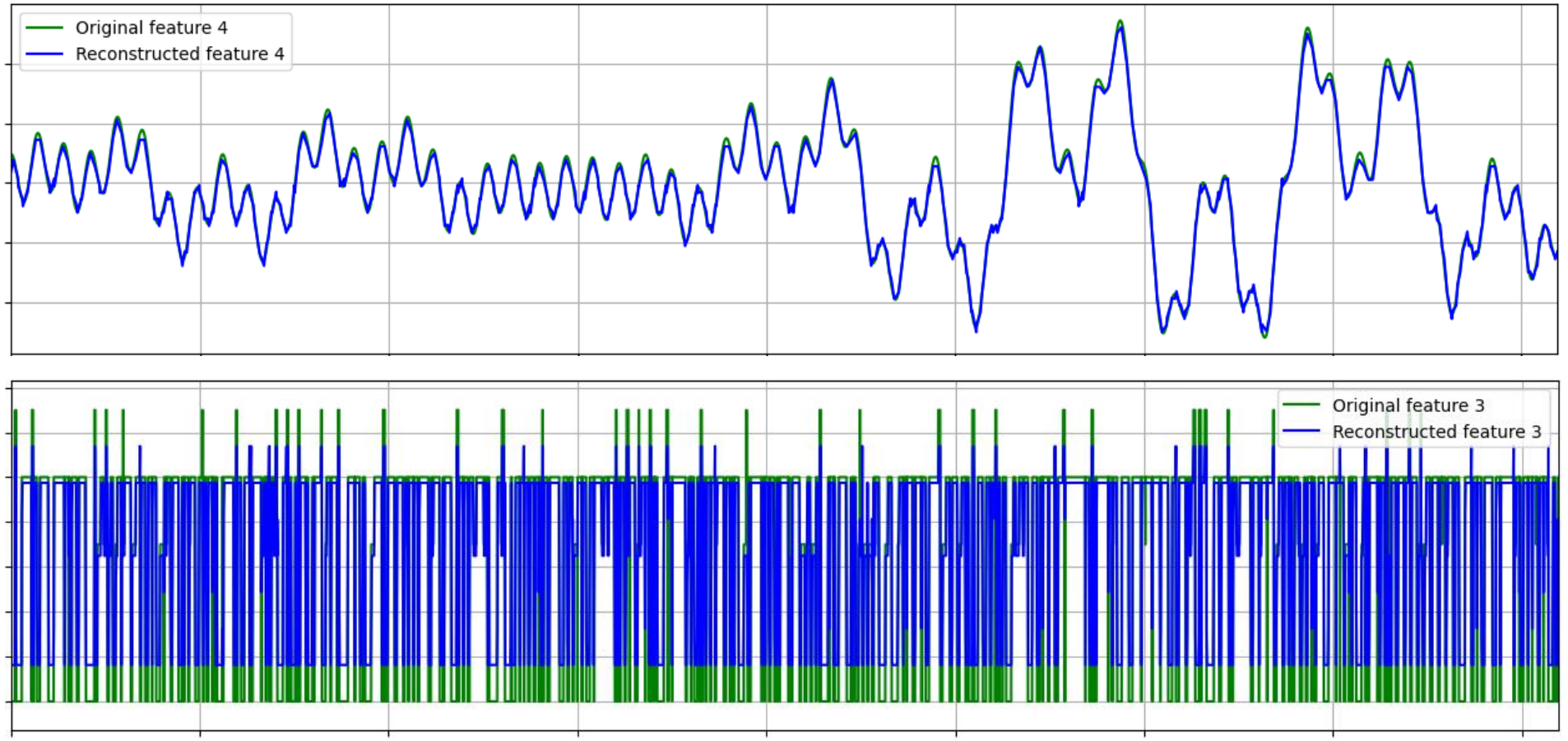


Evaluation: Pulse-width modulation (PWM)

What is the best algorithm?

LIF	SF
PWM	BSA

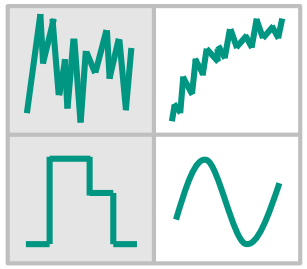


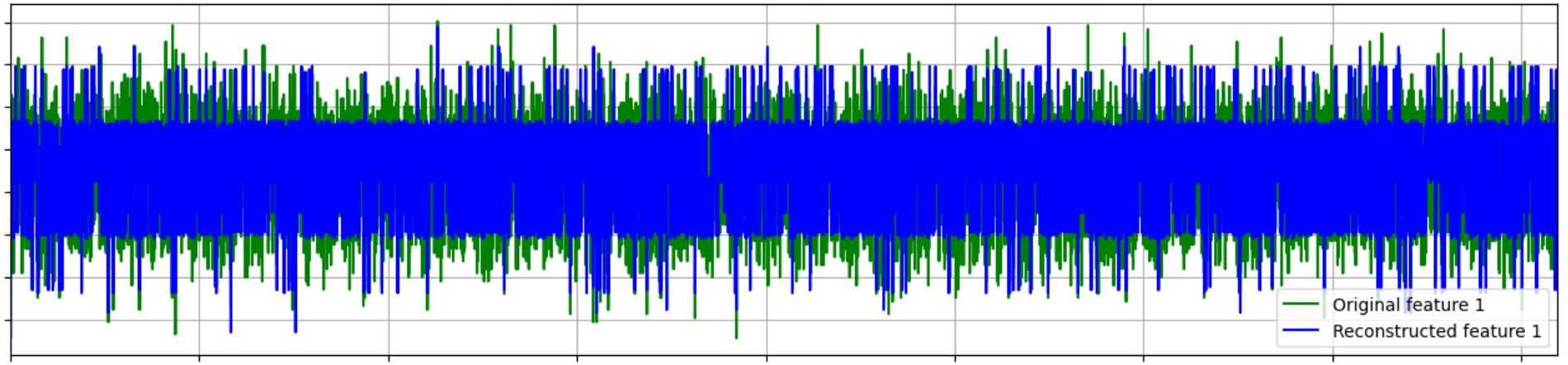


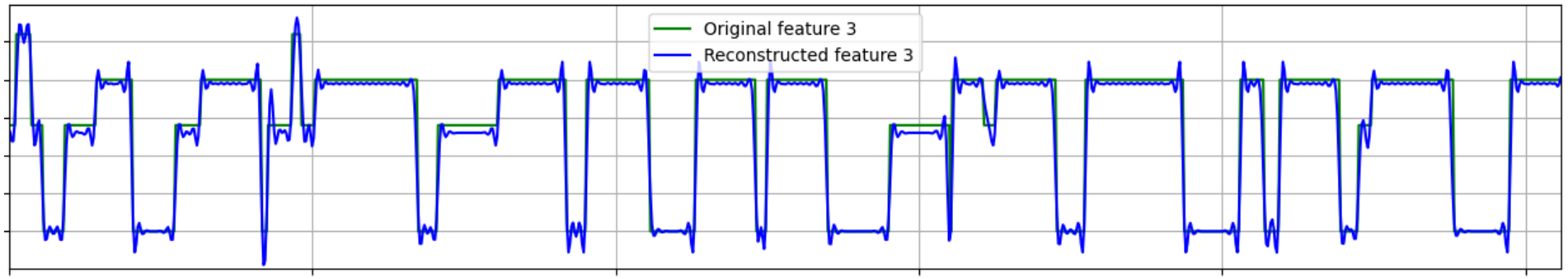
Evaluation: Ben's spiker algorithm (BSA)

What is the best algorithm?

LIF	SF
PWM	BSA

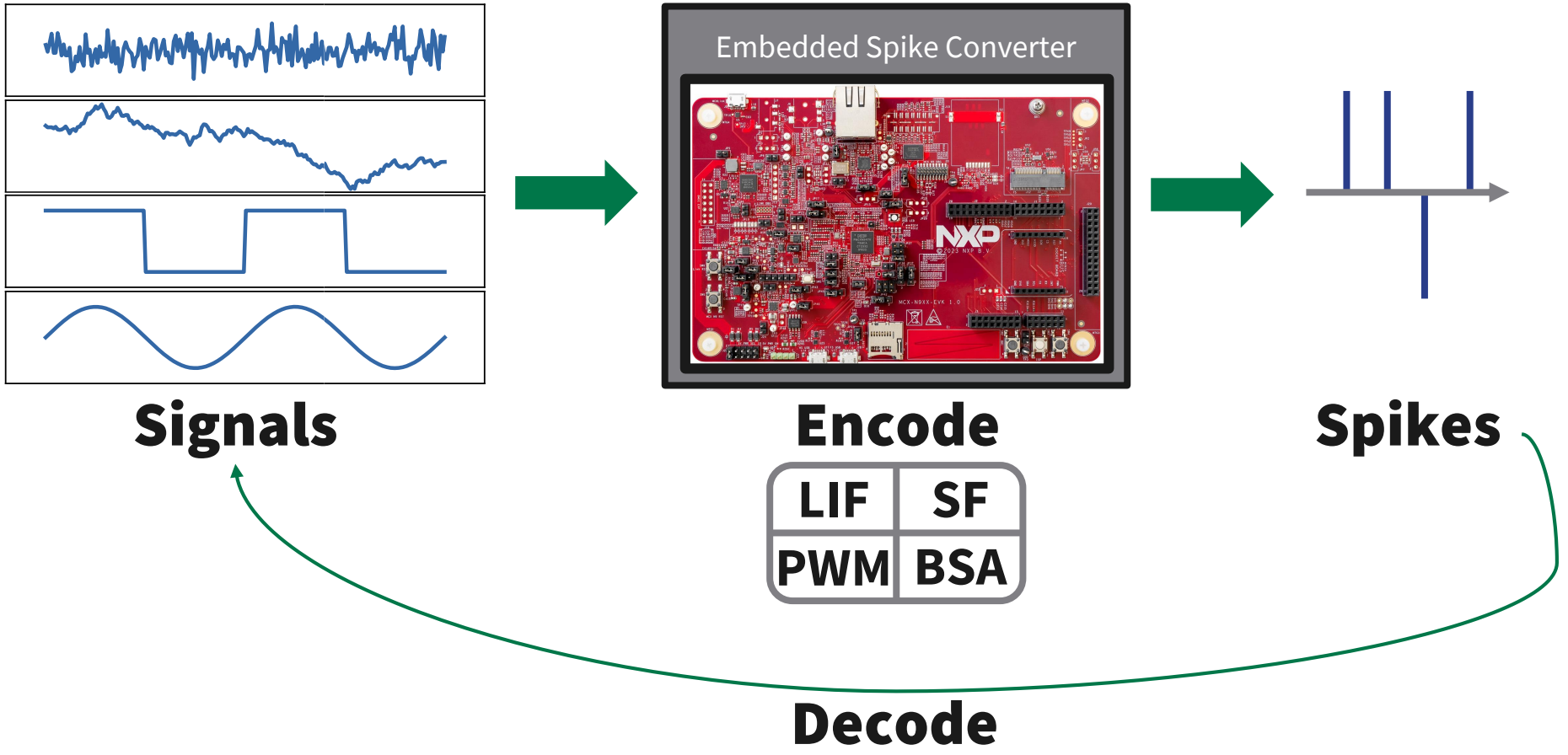






Evaluation

What is the best algorithm? Time Power Energy Sparsity Error



Evaluation

What is the best algorithm?

- Best Error: **SF** — Worst: **PWM**
- Best Sparsity: **PWM** — Worst: **BSA**
- Best Time: **SF** — Worst: **BSA**
- Best Power: **SF** — Worst: **BSA**
- Best Energy: **SF** — Worst: **BSA**

Encoding Method	LIF	SF	PWM	BSA
Error (MSE)	0.17	**0.16**	0.32	0.23
Sparsity (%)	51.9	30.6	**17.7**	53.1
Time (s)	0.13	**0.12**	0.69	2.24
Power (nW)	9.71	**6.87**	11.4	20.0
Energy (pWh)	0.34	**0.24**	2.19	12.4

Spike Encoding Repository

github.com/Alex-Vasilache/Spike-Encoding

Encoding

```
signal = tensor([0.0, 0.2, 0.4, 0.2, 0.0])

sf = StepForwardConverter(threshold=0.1)
spikes = sf.encode(signal)
```

Decoding

```
sf.decode(spikes)
```

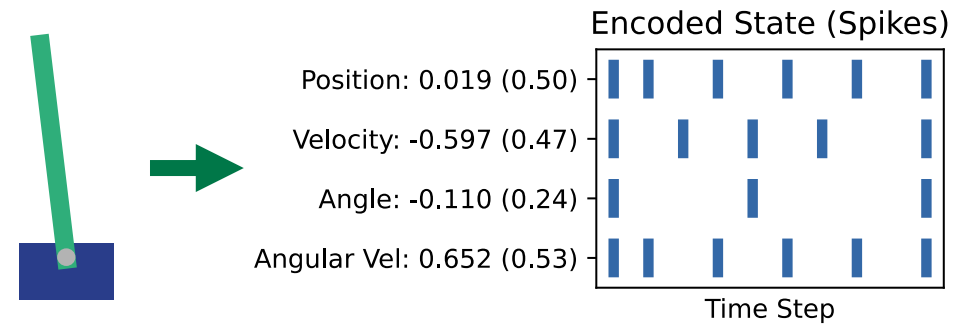
Optimization (minimize reconstruction error)

```
threshold = sf.optimize(signal)
```

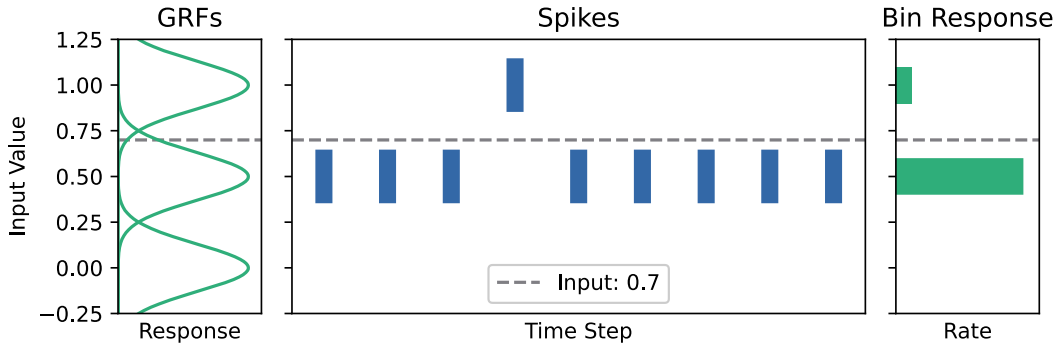
Supported Algorithms

- LIF-based encoding (LIF)
- Step-forward encoding (SF)
- Pulse-width modulation (PWM)
- Ben's spiker algorithm (BSA)
- Gymnasium encoder
- Bin encoder

Gymnasium Encoder

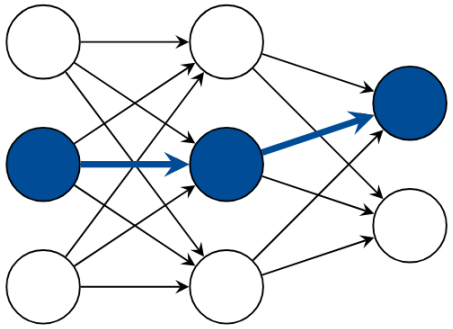


Bin Encoder

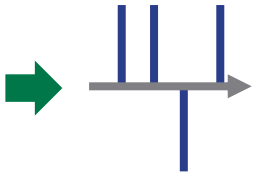


Conclusion

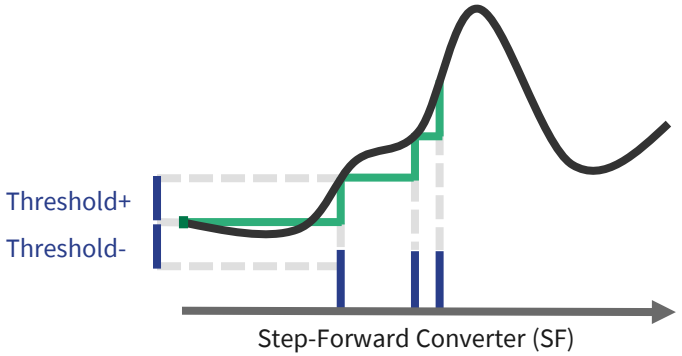
Spike Encoding Framework



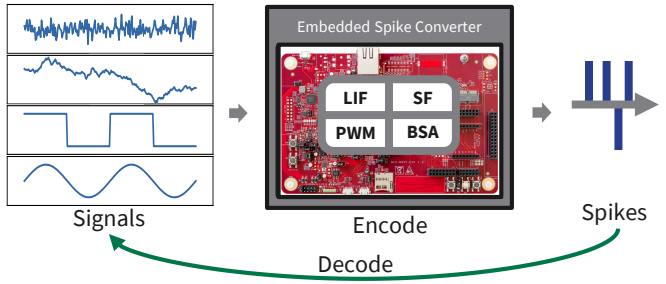
SNN



Spikes



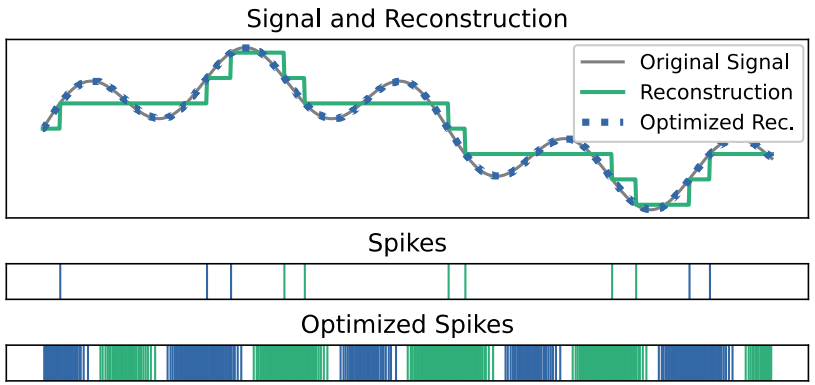
Encoders



Embedded Evaluation

Encoding Method	LIF	SF	PWM	BSA
Error (MSE)	0.17	**0.16**	0.32	0.23
Sparsity (%)	51.9	30.6	**17.7**	53.1
Time (s)	0.13	**0.12**	0.69	2.24
Power (nW)	9.71	**6.87**	11.4	20.0
Energy (pWh)	0.34	**0.24**	2.19	12.4

Results



Supported Algorithms

- LIF-based encoding (LIF)
- Step-forward encoding (SF)
- Pulse-width modulation (PWM)
- Ben's spiker algorithm (BSA)
- Gymnasium encoder
- Bin encoder

Repository

Thank You!

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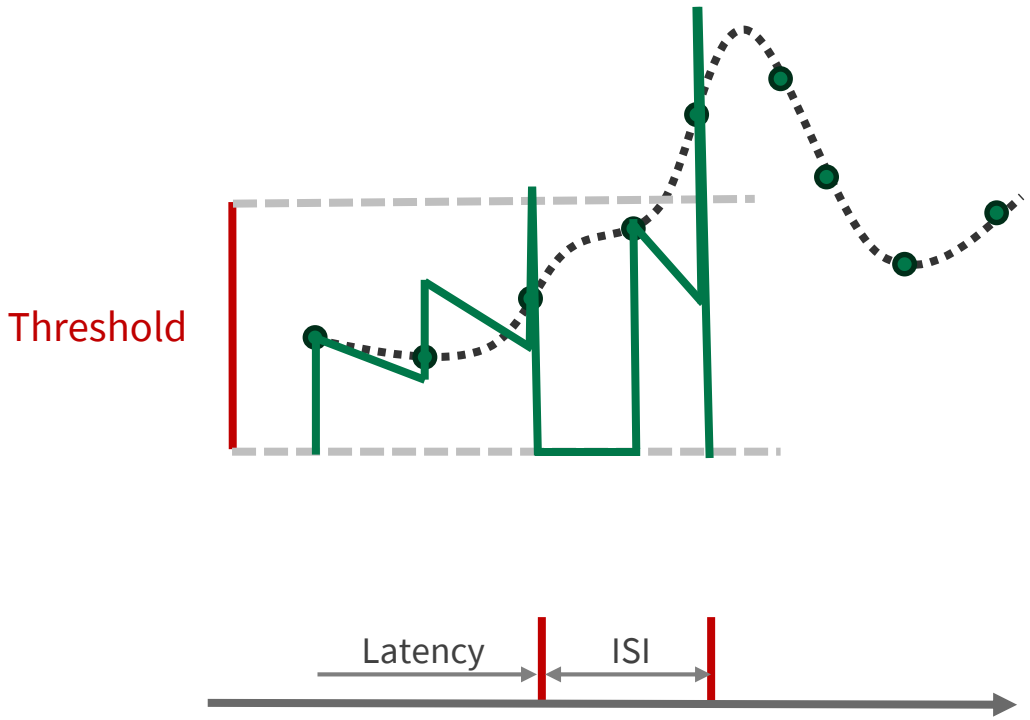
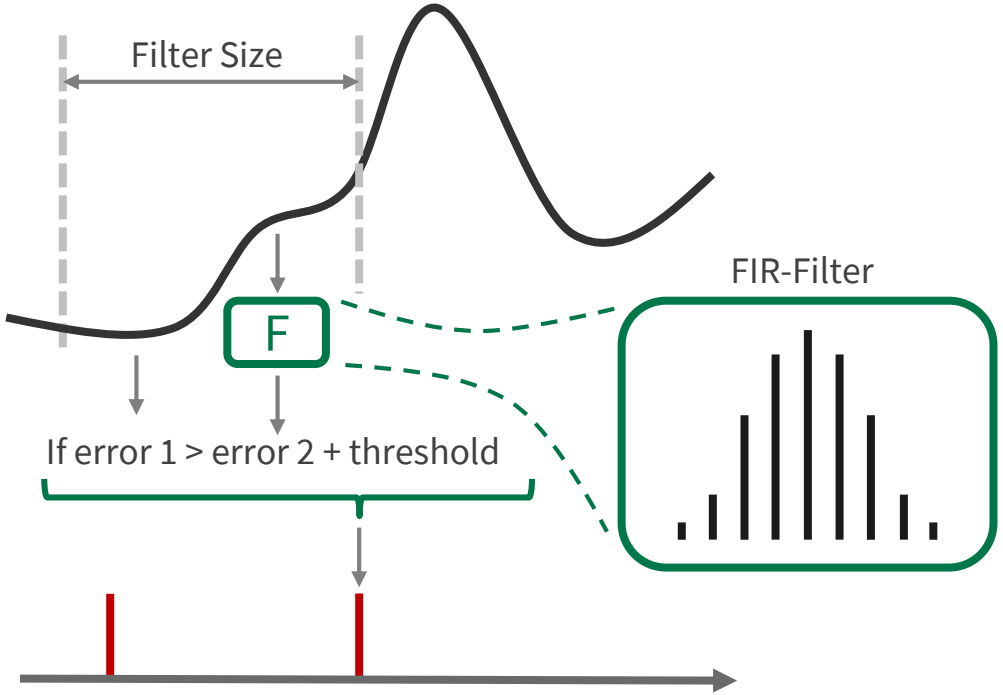
Spike Encoding Algorithms

Leaky Integrate and Fire encoding (LIF) and Bens Spiker Algorithm (BSA)



Leaky Integrate and Fire (LIF)



Ben's spiker algorithm (BSA)