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Enabling Ultra-low Power Machine Learning at the Edge

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Spike-based Beamforming using pMUT Arrays for Ultra-Low Power Gesture Recognition

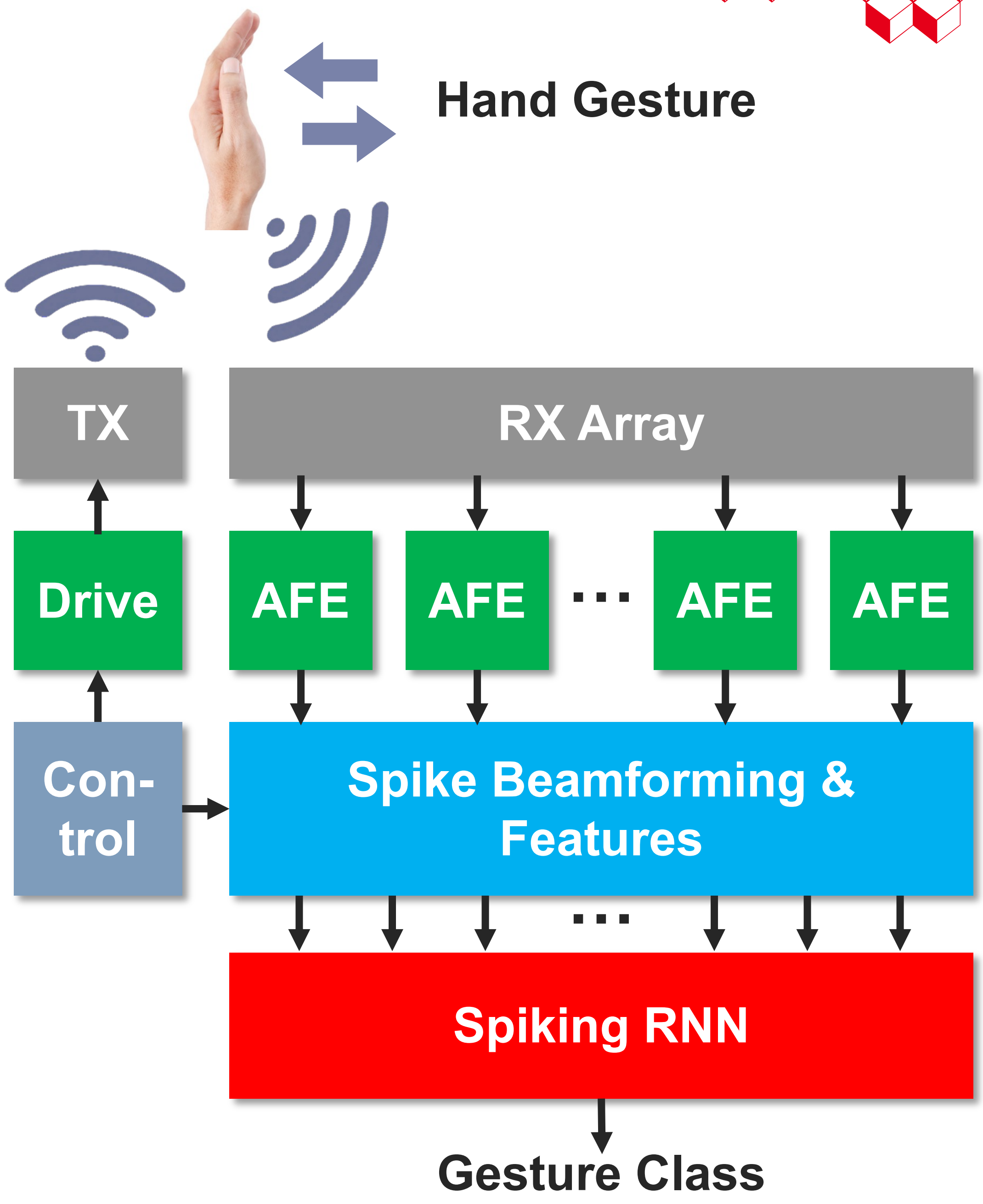
Emmanuel Hardy

System Overview

› **End-to-end Ultrasonic Gesture Recognition with pMUTs**

› **Competing technologies:** IR, electric field, radar, camera.

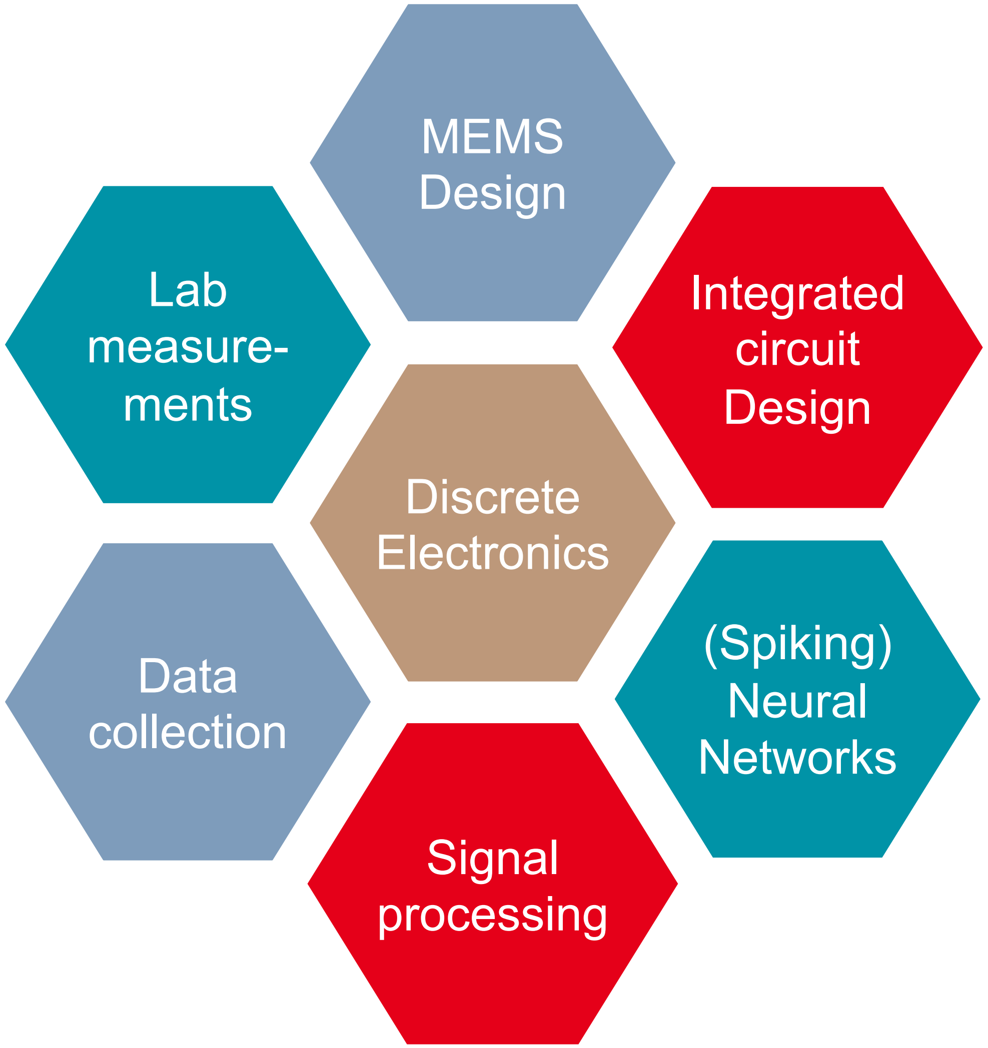
› **Key advantages:**
  - Insensitivity to light/shadow
  - Low cost
  - Low power



Key Points

› **End-to-end Power Efficient Edge AI device**
  - Efficient sensors
  - Analog-to-information conversion
  - Low power inference

› **Needs a widely cross-functional team**



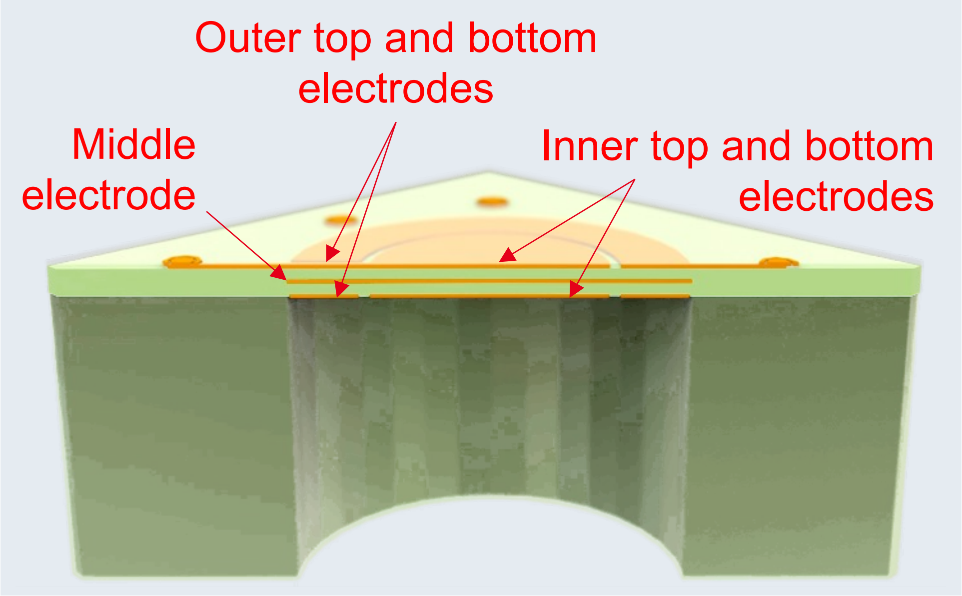
The team

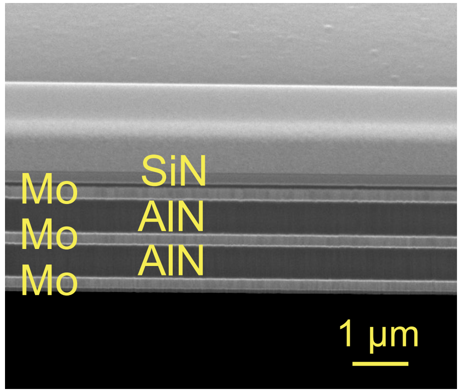
- Bruno Fain
- Thomas Mesquida
- François Blard
- François Gardien
- François Rummens
- Jean-Claude Bastien
- Jean-Rémi Chatroux
- Sébastien Martin
- Venceslass Rat
- Elisa Vianello

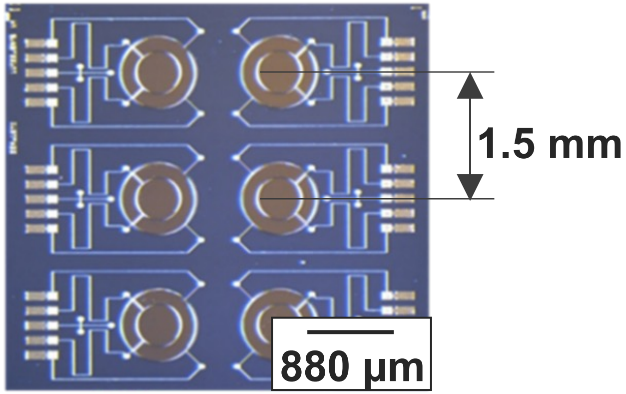
E. Hardy *et al.*, “Spike-based Beamforming using pMUT Arrays for Ultra-Low Power Gesture Recognition,” in *2022 IEDM*, Dec. 2022,
doi: 10.1109/IEDM45625.2022.10019395.

1. Sensor Array

PMUTs Transducers







PMUT: Piezoelectric Micromachined Ultrasonic Transducer

- Aluminum nitride piezo material
- Bimorph structure for higher sensitivity and TX power
- Resonance ~ 100kHz (tunable)
- 8” MEMS production line in CEA-Leti

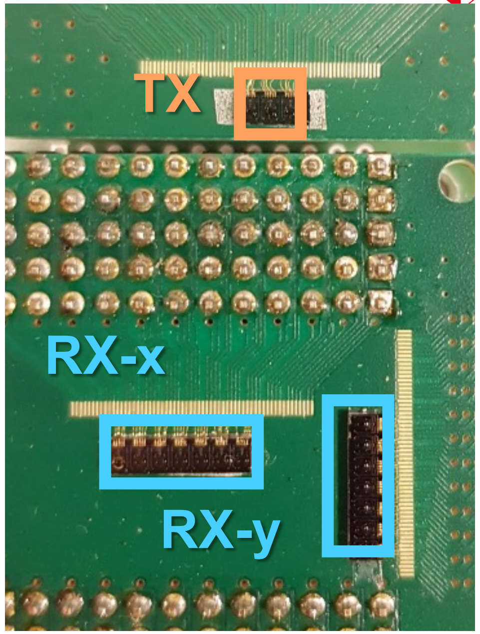
Acoustic setup

› **TX:** 1 PMUT

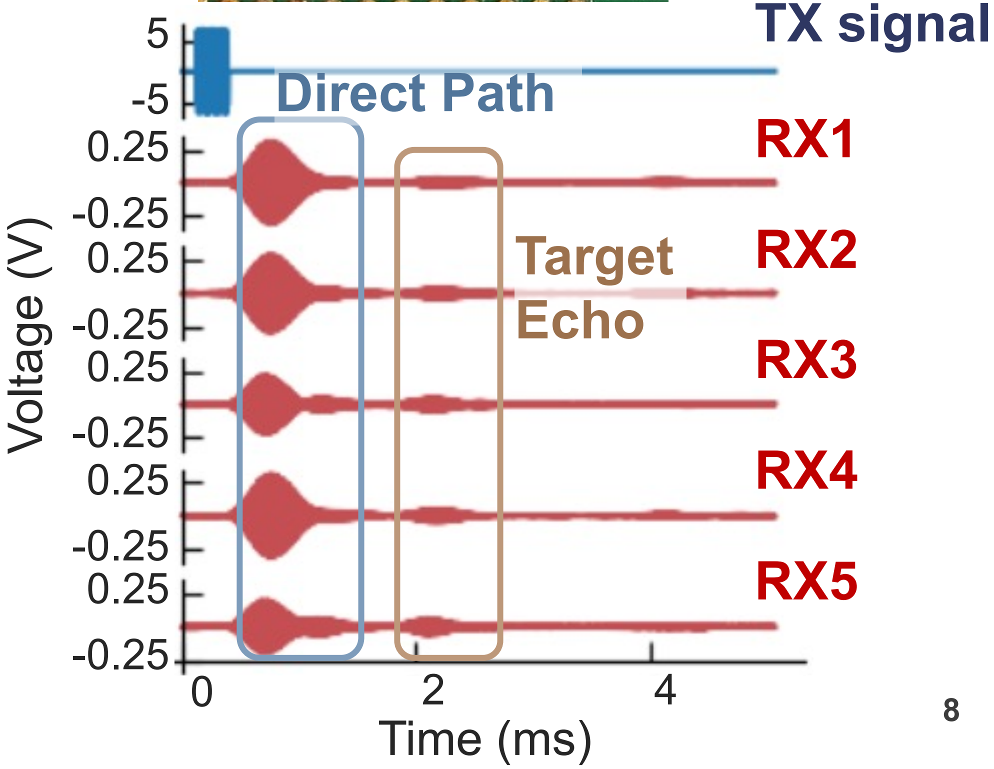
› **RX:** 2 orthogonal arrays of 5 PMUTs

✓ **3D sensing**

› **Range:** 10 -> 60 cm

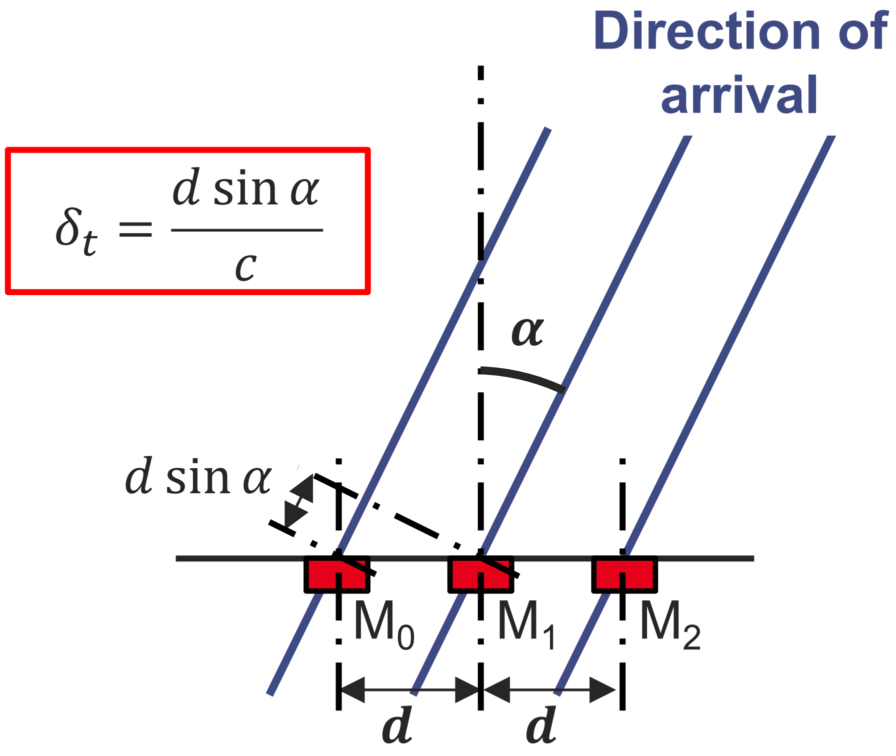


PMUT Arrays

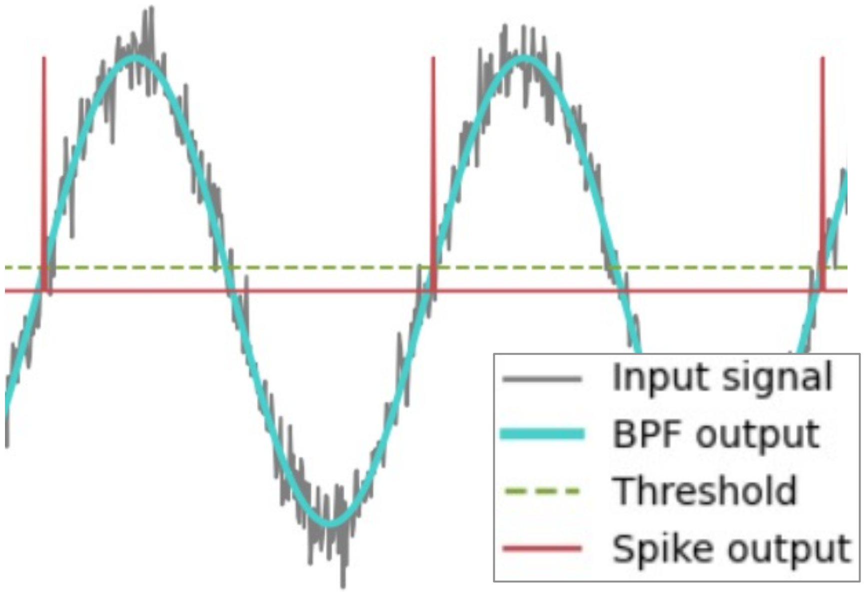


2. Spike-based signal processing

Spike-based Beamforming

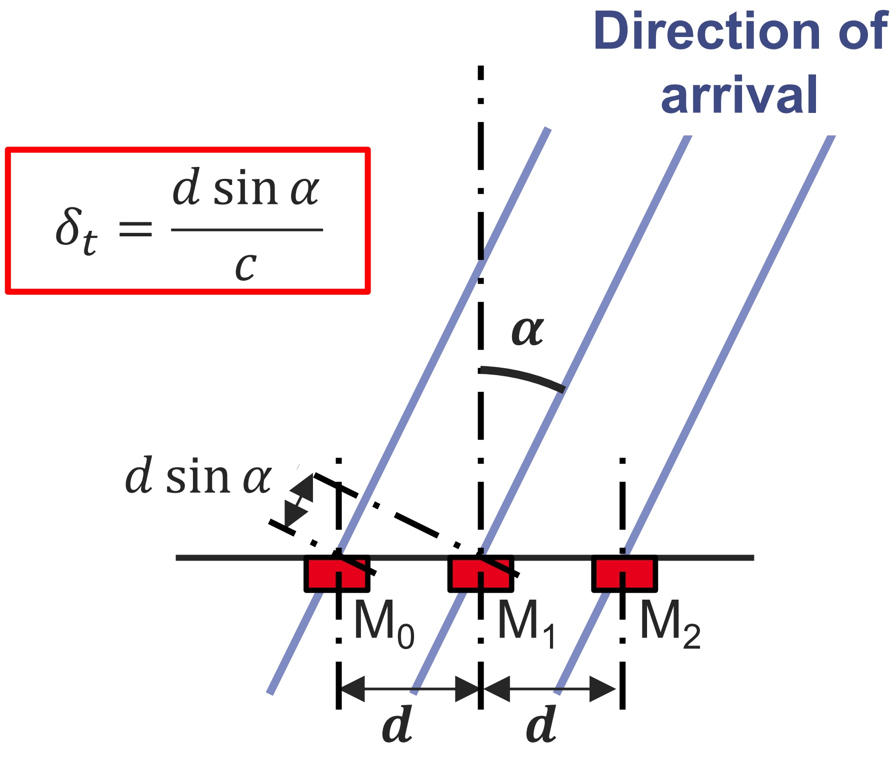


Time Difference of Arrival between M_0 and M_1

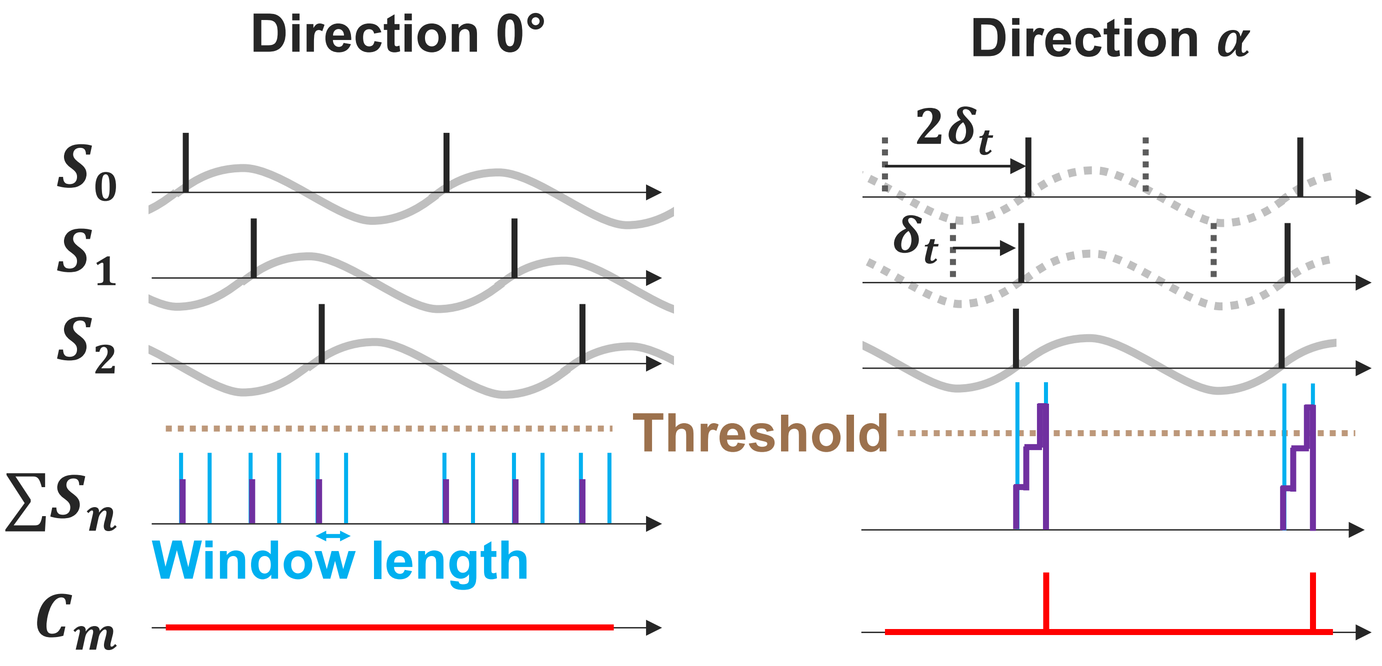


Conversion to spikes

Spike-based Beamforming



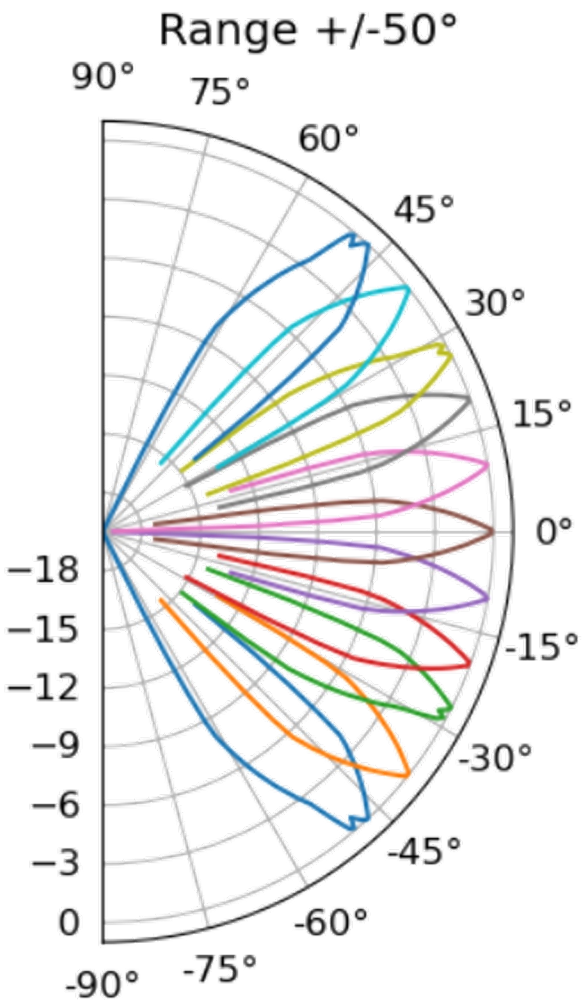
Time Difference of Arrival between M_0 and M_1



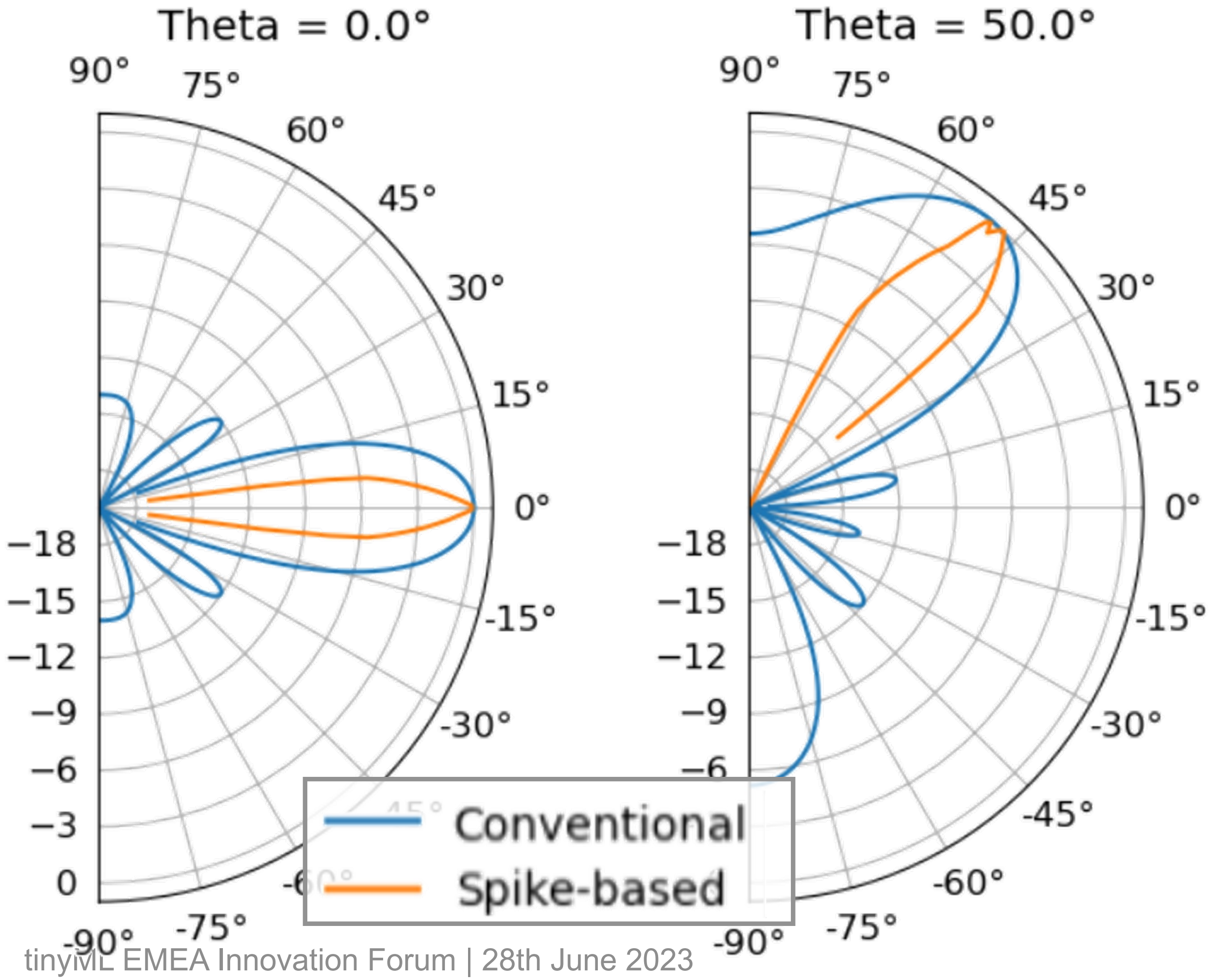
Spike Coherence Detection

Spike-based Beamforming

- 11 directions
- +/-50° range with 10° steps
- Optimal threshold and window size

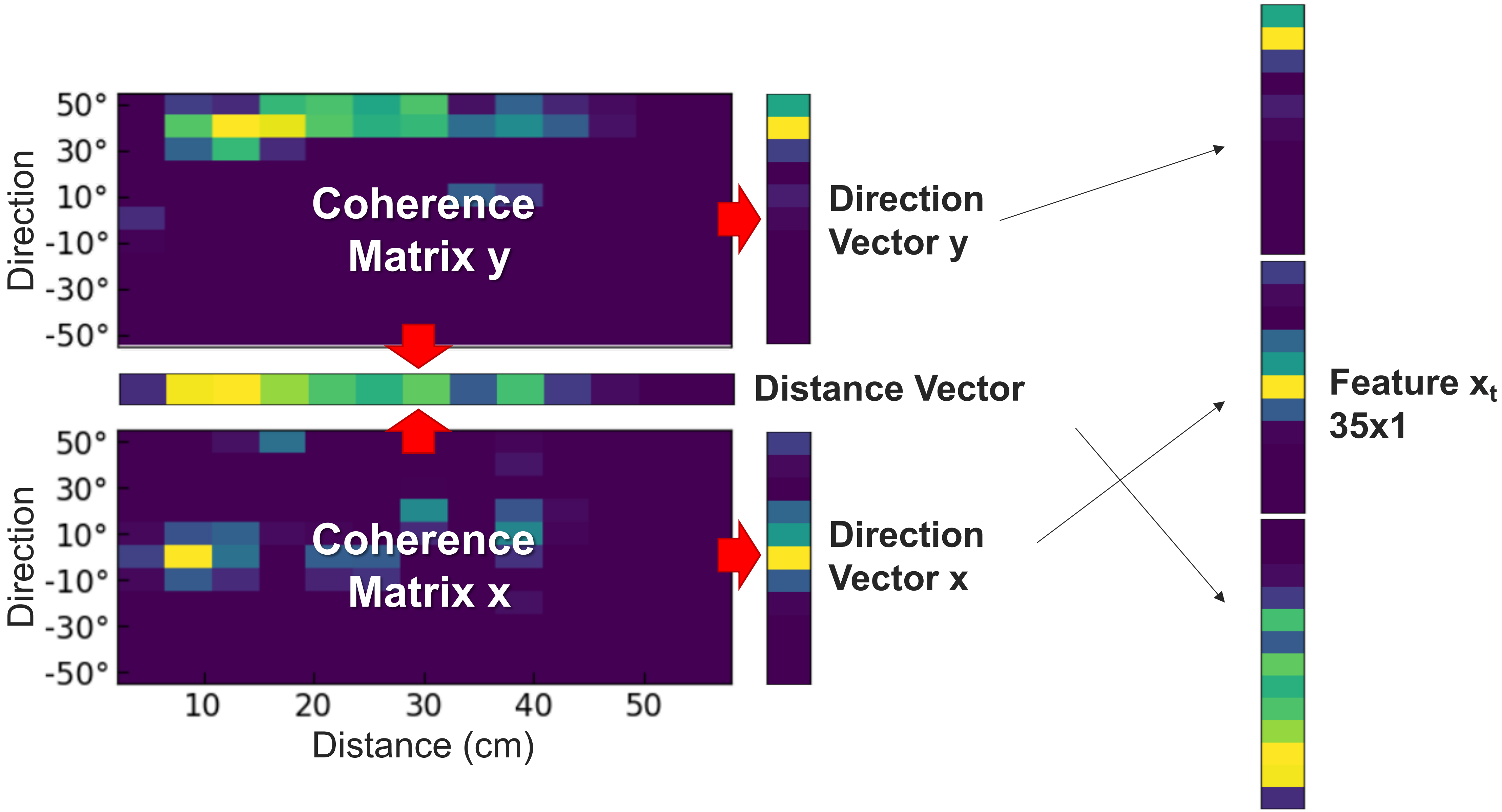


Spike-based Beamforming

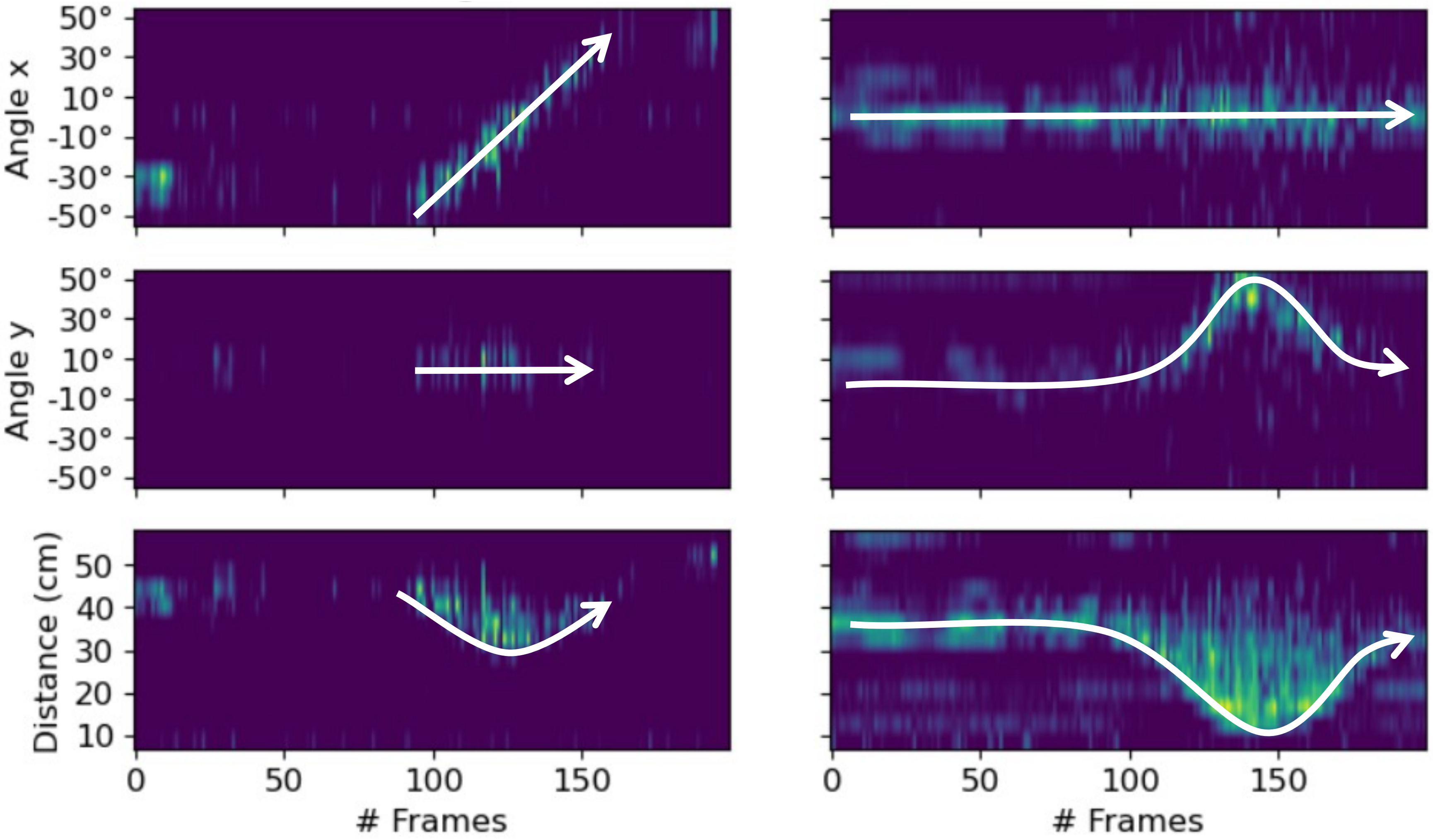


- **wrt. Conventional Beamforming**
  - ~3 times better angular selectivity at 0°
  - No side lobes
  - Increased range
- **BUT not proportional to signal amplitude.**

Feature Vector



Example of Gestures

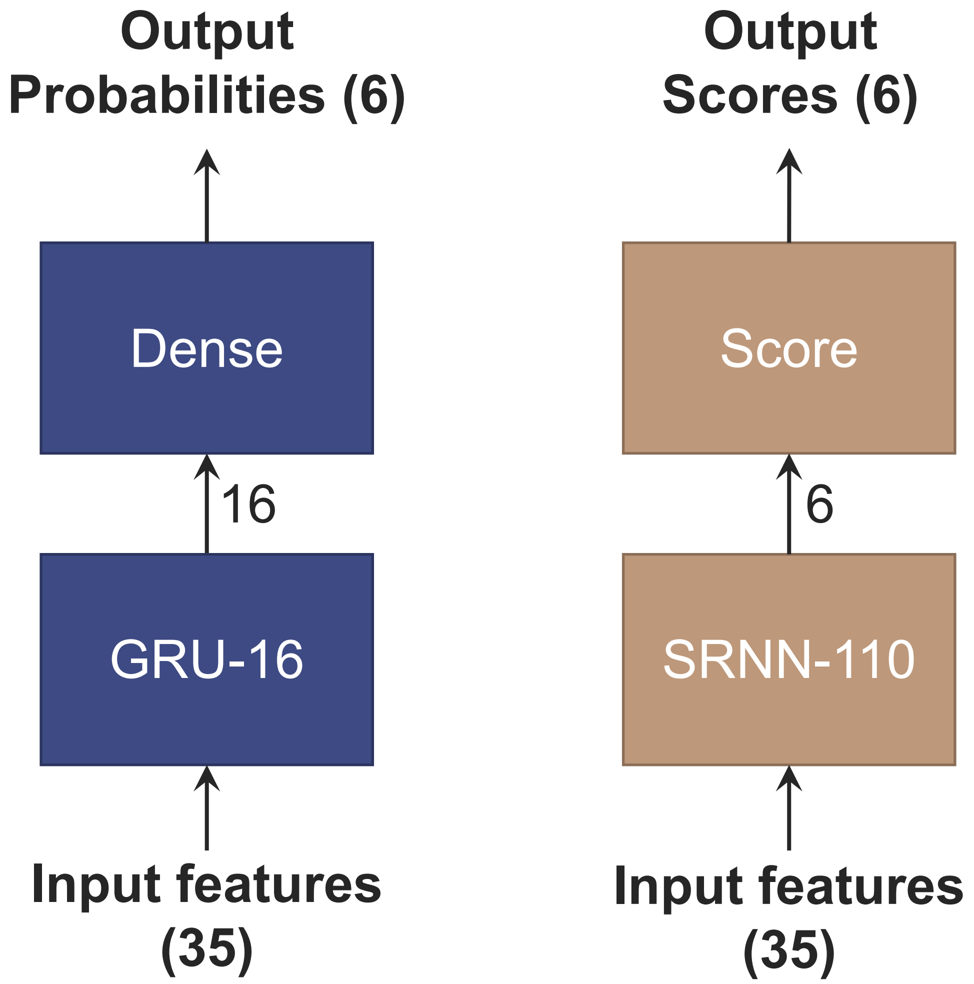


3. Classification & Results

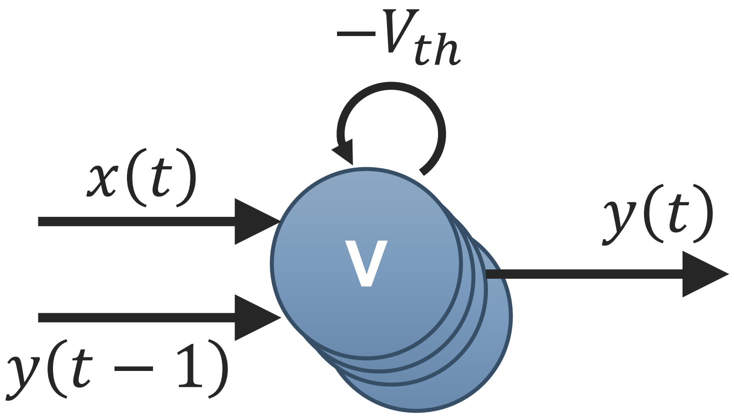
Gesture Classifier

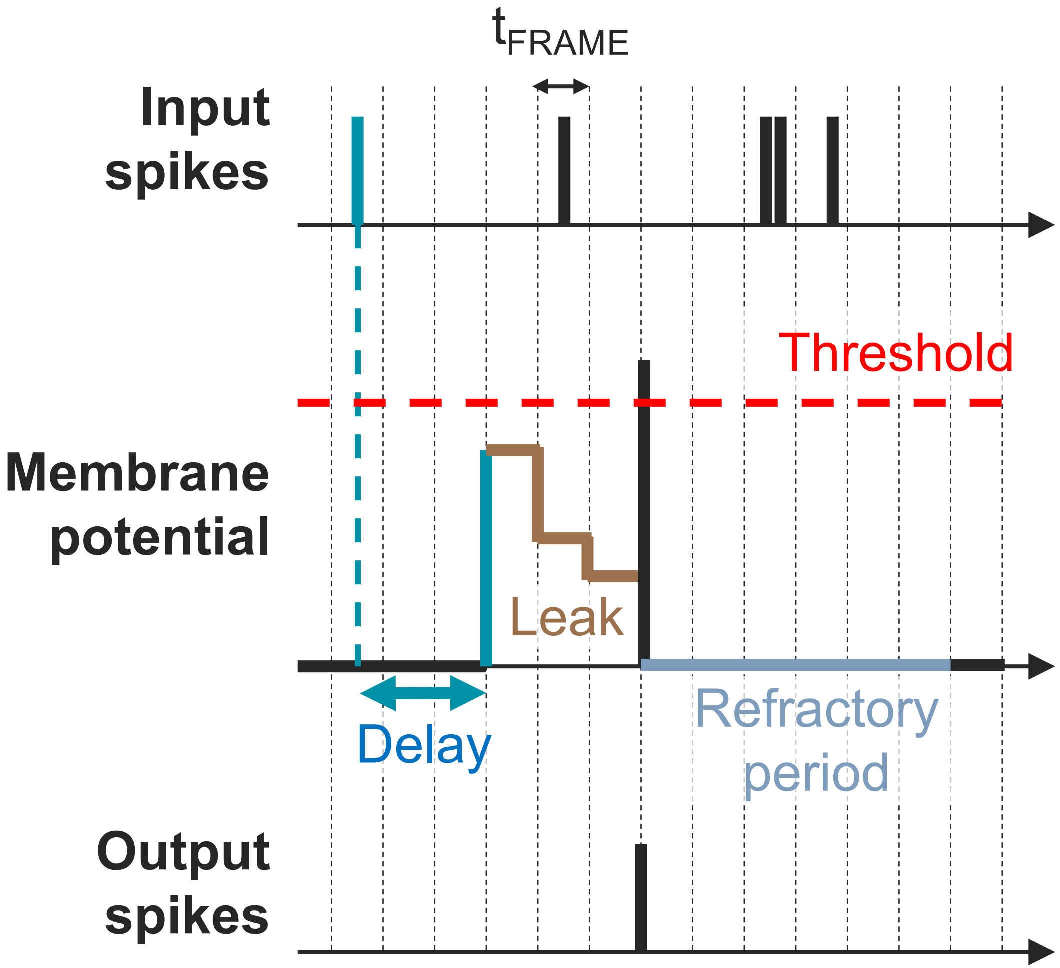
› **Recurrent Neural Network**
- Trainable Temporal Dependency (no fixed window)
- Computational Efficiency

› **Two classifiers:**
1. GRU Baseline
2. Spiking RNN Hardware Target

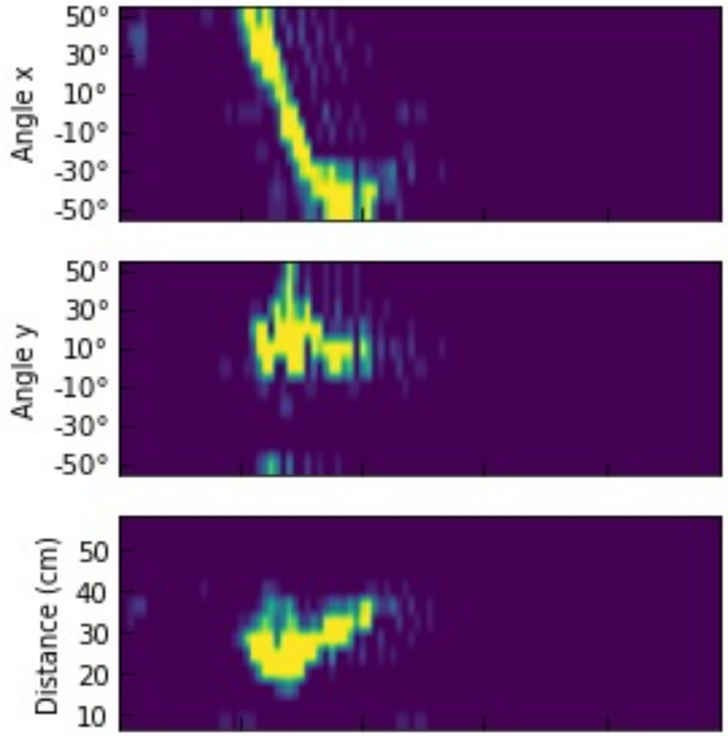


Spiking Recurrent Unit



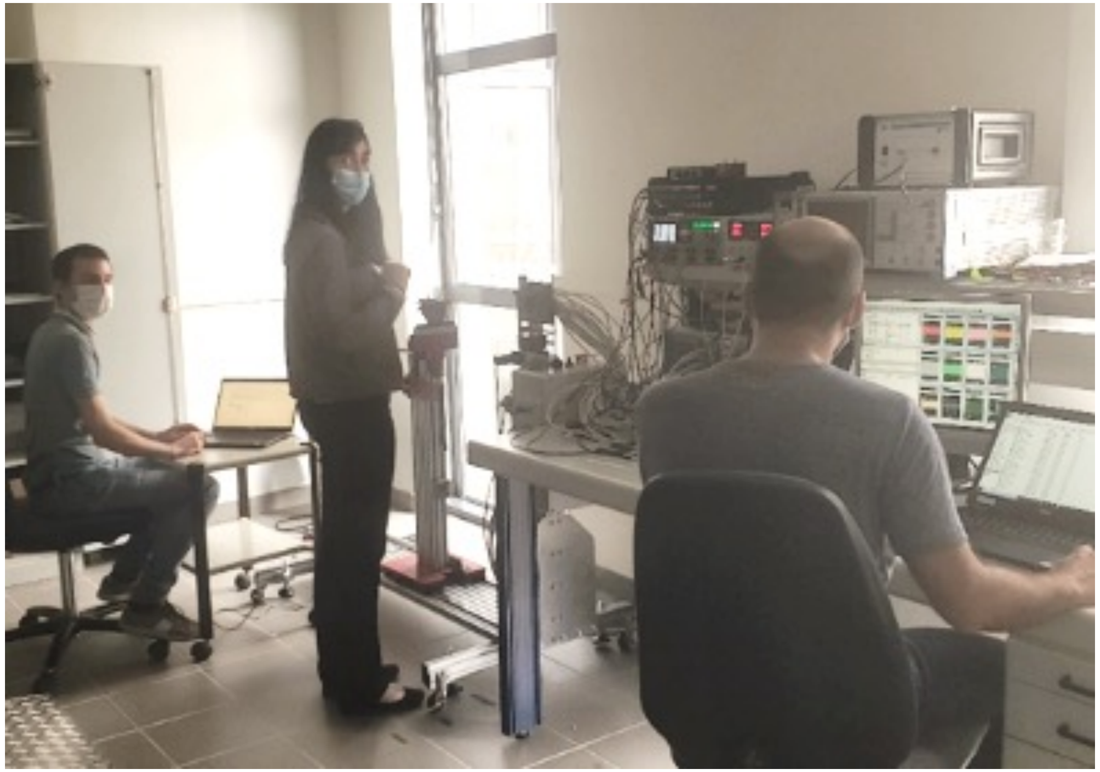


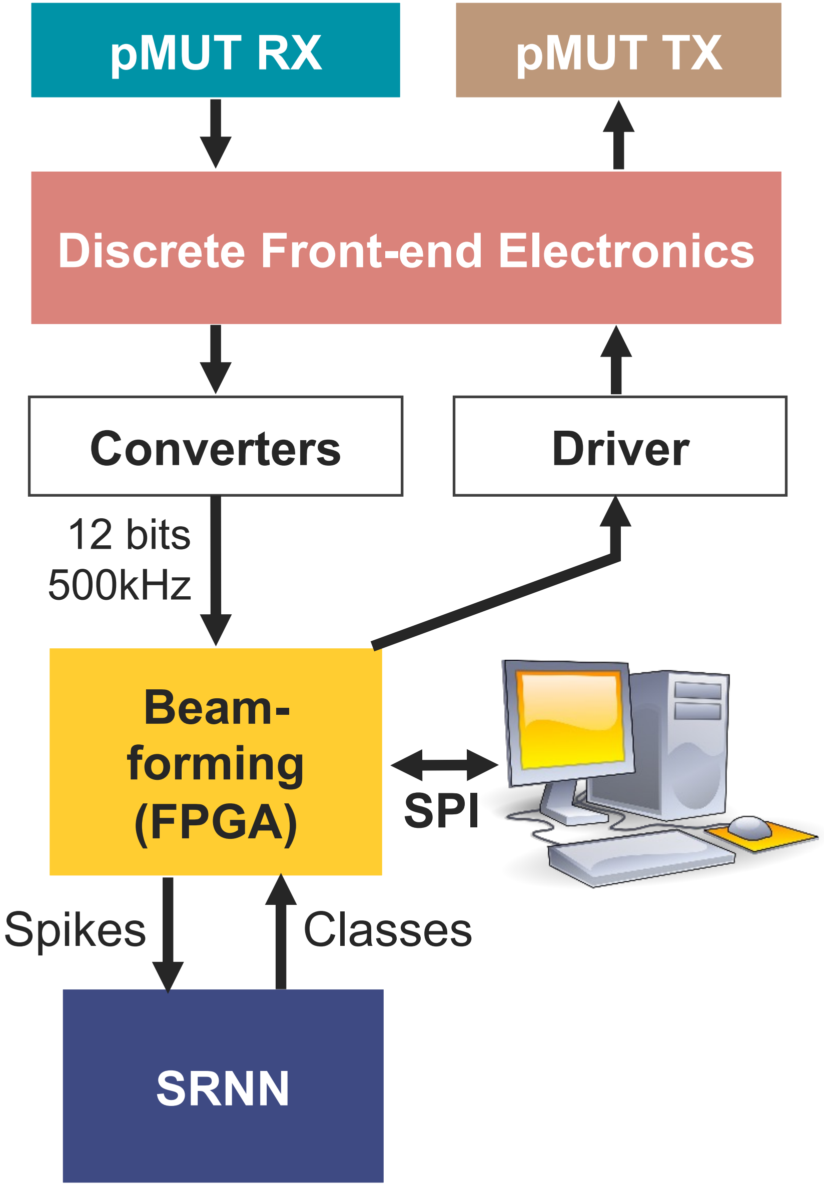
Right-Left example



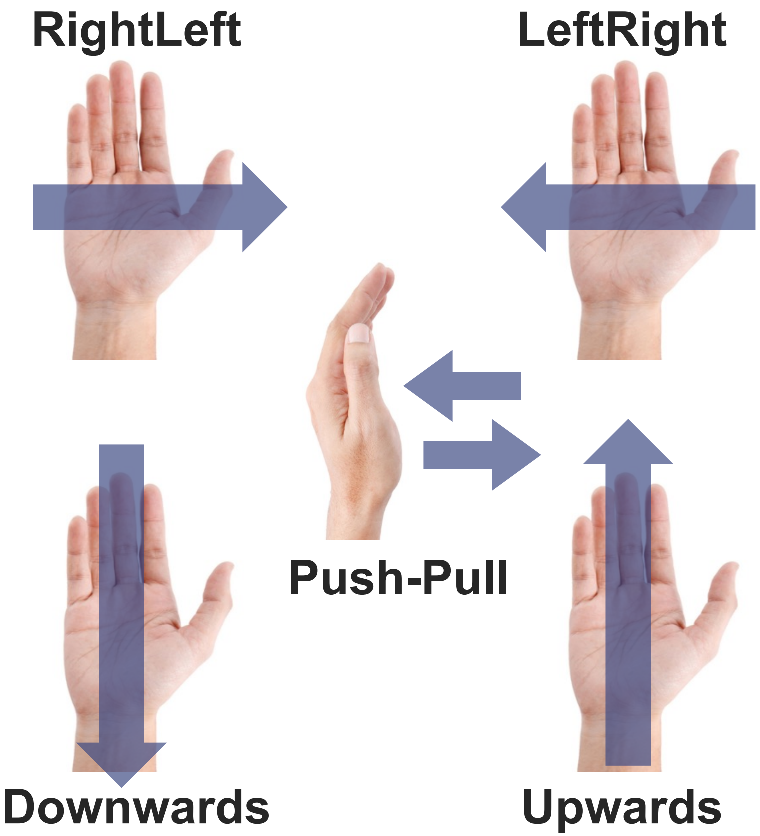
4 bits Feature Quantization

Experimental Setup



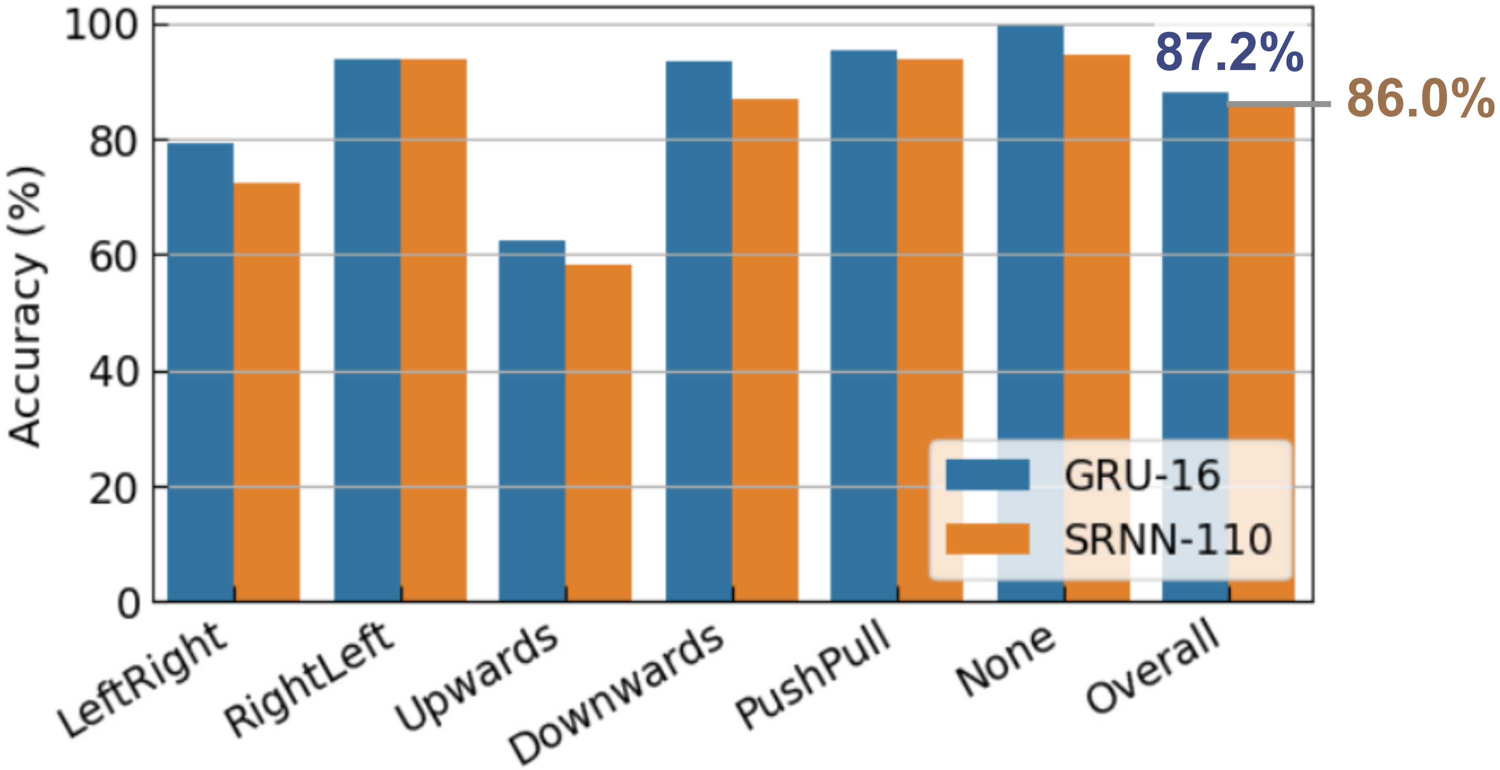


Gesture Dataset



- 5 gestures + None class
- 499 examples, 12 participants
  - Training/test (9/3 split)
- 10 to 50 cm distance
- Data augmentation for training
  - System symmetry

Classification Results



Small accuracy drop with SRNN

Classification Results

Predicted

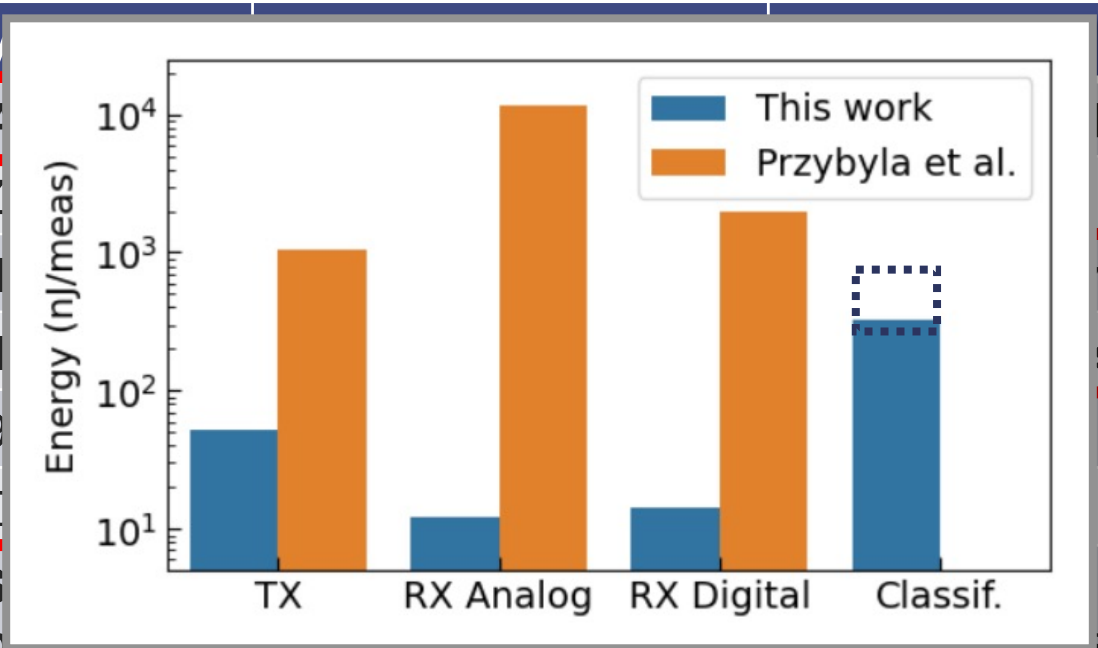
True

True \ Predicted	LeftRight	RightLeft	Upwards	Downwards	PushPull	None
LeftRight	72.4%	0.0%	0.0%	3.4%	10.3%	13.8%
RightLeft	0.0%	93.8%	0.0%	0.0%	0.0%	6.2%
Upwards	0.0%	4.2%	58.3%	0.0%	29.2%	8.3%
Downwards	0.0%	0.0%	0.0%	86.7%	6.7%	6.7%
PushPull	1.6%	0.0%	0.0%	0.0%	93.7%	4.8%
None	0.0%	0.0%	0.0%	0.0%	5.4%	94.6%

Gesture ambiguity, small dataset

State-of-the-Art

	This work	Przyby		.
Type of transducers	TX-RX: AIN pMUT	TX-RX: A		TS
# RX - Pattern	10 - 2 Lines X/Y	7 - Z		
Classif. type	SRNN	N		est
Accuracy	86.0% (5 gest.)	N		st.)
Meas. period	40 ms	5.9		
Max. range	60 cm	100		
Hardware integration	COTS	AS Post-p		Post-process
Est. sensing energy (ASIC)	78.1 nJ/meas.	15.6 µJ/meas.	Not measured	Not measured
Est. inference energy (ASIC)	330/760 nJ/meas. (None/Gesture)	N/A	Not measured	Not measured



Wrapping Up…

Applications and Perspectives

- **Gesture Recognition**
  - Wearables, automotive, VR headsets.

- **Robotics**
  - Obstacle detection
  - Beamforming at emission

- **What's Next**
  - Apply this approach to new sensors from CEA Leti
  - Build new exciting prototypes and ASICs

Takeaway Points

1. Small form factor pMUT array
2. Beamforming & Signal Processing in the Spike domain
3. Low Power Gesture Classification

Analog-to-Information strategy to yield more efficient Sensors + Edge AI systems.

Thank you!

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