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Future Computing Laboratory

Opening the Stack: An Open-Source Journey from Wearable Biosignal Acquisition Platforms to Edge Intelligence

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IEEE EMBC 2026

48TH ANNUAL International conference of the IEEE Engineering in Medicine and Biology Society

26-30 July 2026

Toronto, Canada

PULP Platform

Open Source Hardware, the way it should be!

@pulp_platform

pulp-platform.org

youtube.com/pulp_platform

Outline

- Connecting the Humans, PULP-based Wearable interfaces for Advance HMIs
- Building Open Wearables with AI Capabilities
- Democratizing Wearable Ultrasound: the WULPUS story

15 minutes break

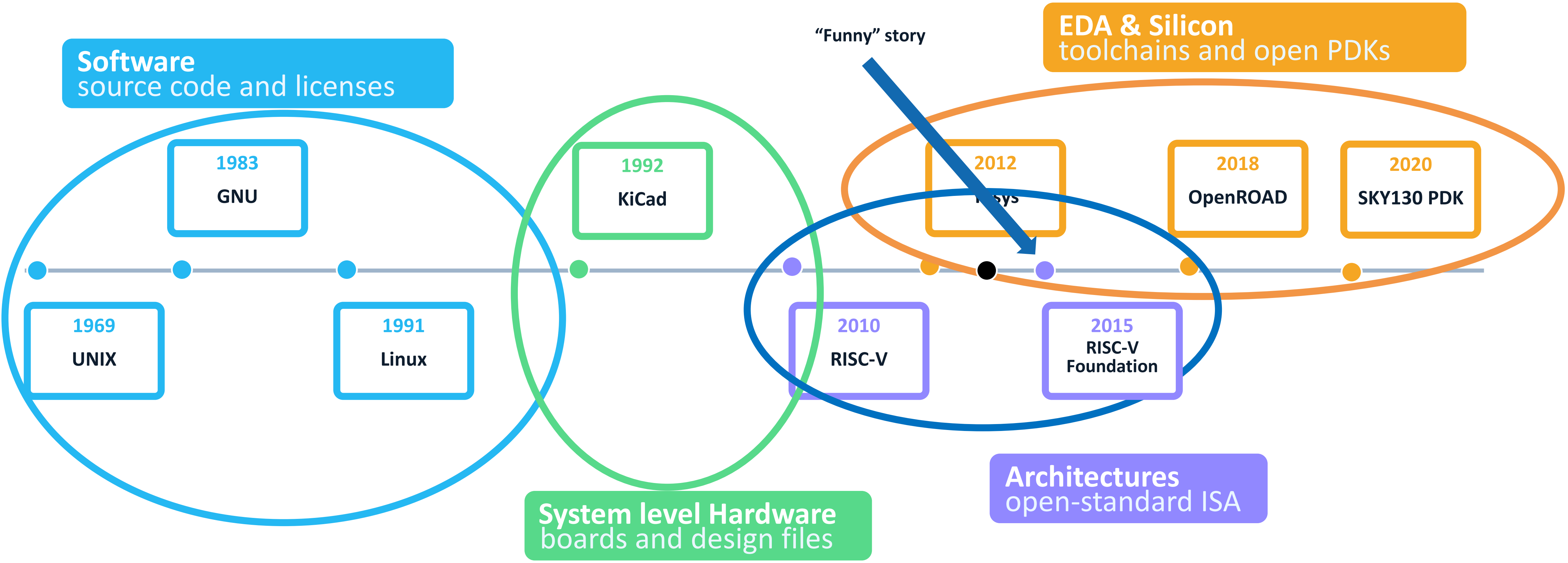
- Accelerating Innovation in Myoelectric Control through Open Software and Standardized Benchmarking
- Open-Source Neuromorphic Chips and Simulation Libraries for Biomedical Applications
- An Open Source, Device-Agnostic GUI for Bio-Signal Acquisition and Processing

Final discussion and hands on

Your background?

- Technical/research
- Commercial
- Biomedical
- Medical/Rehabilitation

Open-source has a long impactful trajectory



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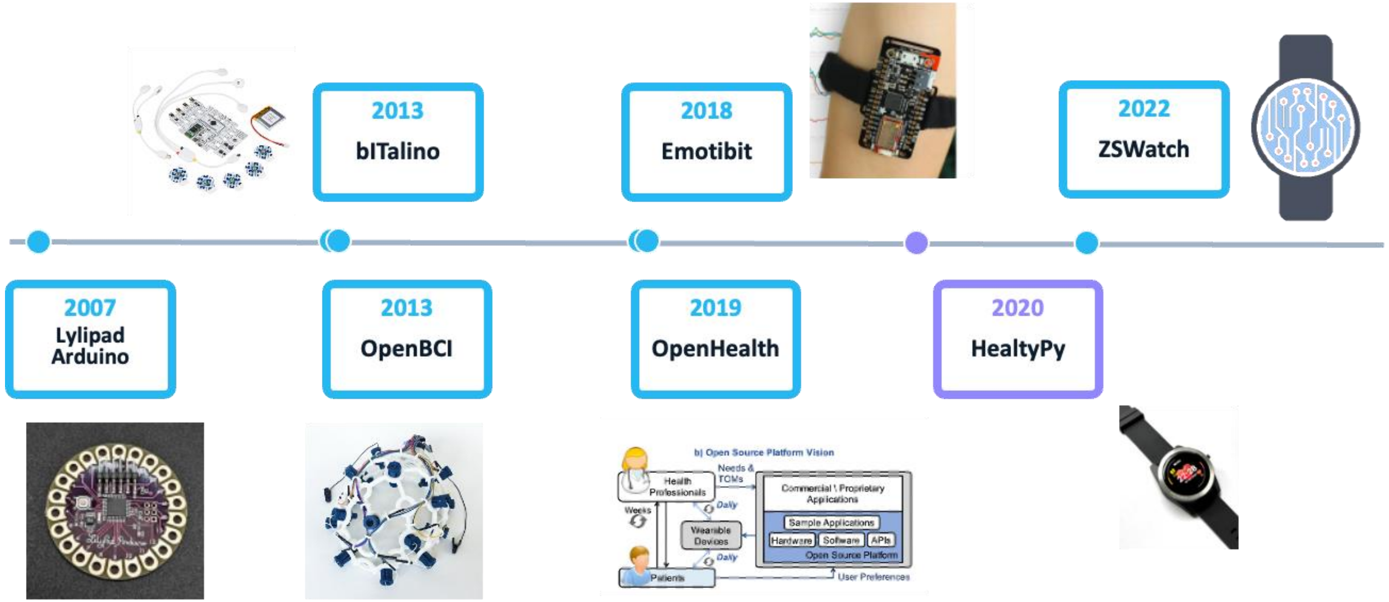
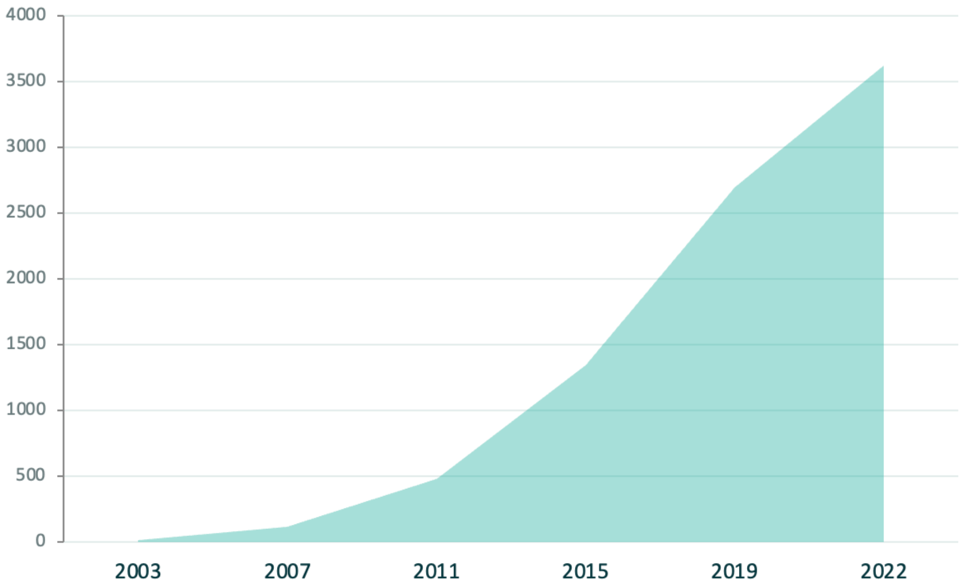
Open-source has a growing hype also in wearables

- **Wearables were gaining traction both in academic research and as commercial devices**
- **So far, we have a growing ecosystem of devices-repositories-datasets-tools**

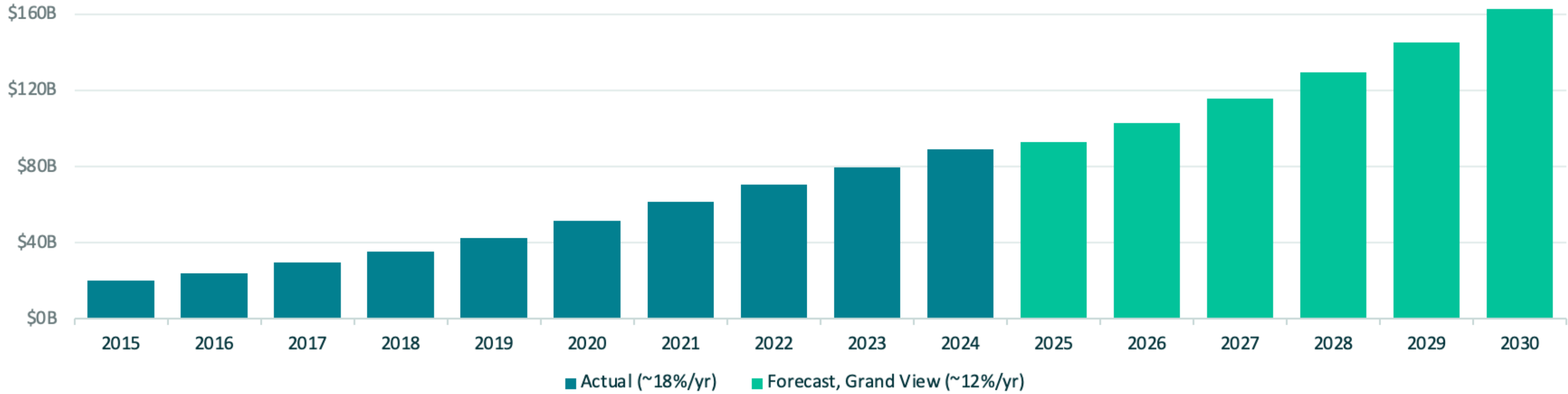




16400+ papers on wearable tech (2003-2022)

Big Techs are investing a lot of effort for wearables

2015 actual	2024 actual	2030 forecast
$20B	$89B	~$163B






Smartwatches: **Apple, Samsung, Garmin, Huawei, Xiaomi, Fitbit (Google)**

Smart Glasses: **Google, Meta-Luxottica , Snap Inc, Vuzix, North (Google)**

Armbands: **Meta, Myo, Scosche, Wahoo**

Smart rings: Oura, Motiv, McLear, Go2Sleep

New ways of **interaction**

A huge amount of ~~data~~

Information

End of story? Not yet!

Commercial devices

- High performance
- Broad availability

- Closed by design

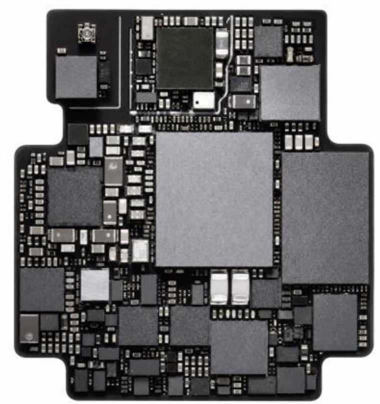
innovation (in wearable devices) greatly benefit from:

- prototype new sensing modalities,
- explore alternative acquisition settings,
- implement custom processing pipelines,
- investigate new interaction paradigms beyond vendor-defined workflows

We have 2 great news!

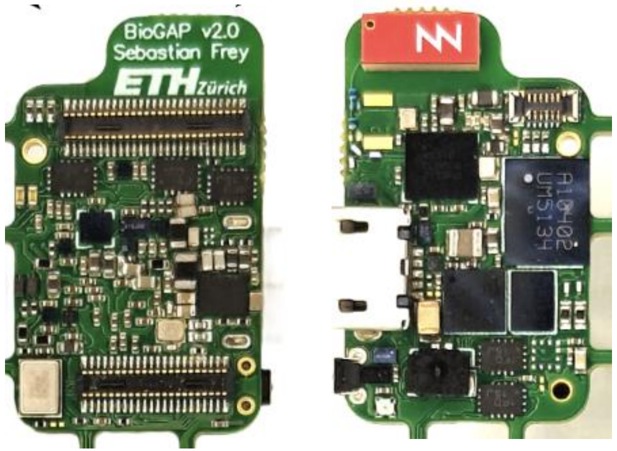
1- Open-source designs are industry-level

Garmin FENIX 7



APPLEWATCH

GAPWATCH



BIOGAP ULTRA

Fully open-source

From the design perspective, we can exploit the same complexity:

- Multilayer board
- BGA components (high level of integration)
- Blind

- Advanced communication stacks

- Libraries for deployment of NNs on embedded processors

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2- We have a full open-source stack

Platforms

- **HW**
- **FW**
- **Mechanical design files**

Algorithms

- **Libraries (C, Python, Matlab)**
- **Implentations (target platforms)**

Frameworks

- **Interfaces for connecting devices**
- **Standardized pipelines**
- **Benchmarking tools**

All of these elements help drive an open-source project forward

Connecting the Humans, PULP-based Wearable interfaces for Advance HMIs

IEEE EMBC 2026
48TH ANNUAL | 26-30 July 2026 | Toronto, Canada

INAIL project — 2013

- NXP Arm Cortex M4
- 16bit SAR ADC
- BT connection
- 4 EMG channels

Cerebro — 2015

- STM32 Arm Cortex M4
- 24bit Sigma Delta
- BT connection
- 8ExG Channels

Biowolf — 2018

- Mr Wolf PULP Chip
- 24bit Sigma Delta
- BLE connection (nRF51832)
- 8ExG Channels

Also with 16 channels: **Biowolf16**

With a PULP chips

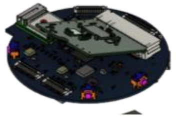
bioGAP — 2023

- GAP9 PULP Chip
- 24bit Sigma Delta
- BLE connection (nRF51832)
- 8ExG Channels
- **Modular Design**

V2 in progress

With a **commercial** PULP chips

GAPWatch — 2024



- GAP9 PULP Chip
- 24bit Sigma Delta
- BLE/WiFI connection
- 16ExG Channels
- PPG
- ECG
- IMU
- Microphone
- **Modular Design**

V2 in progress

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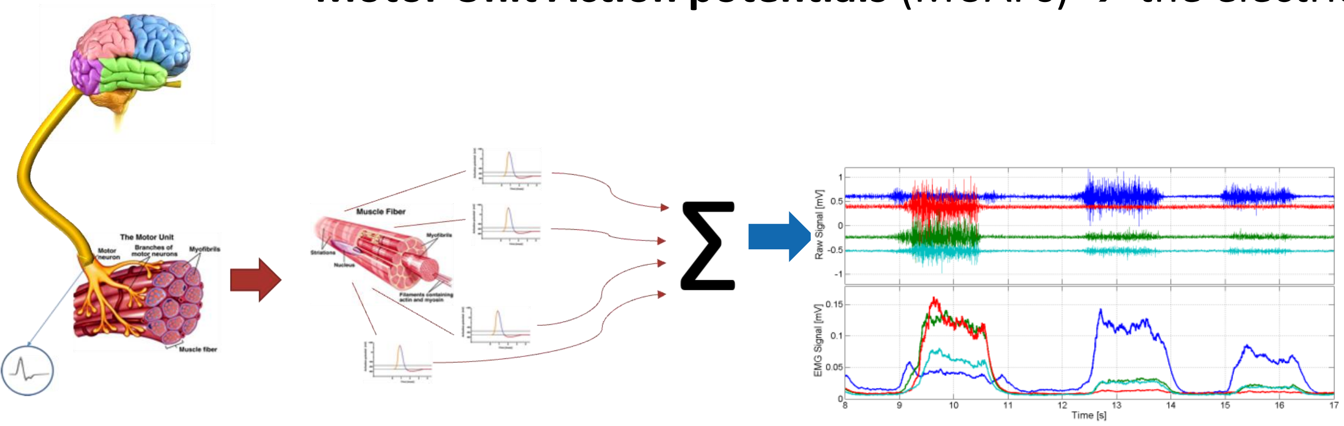
A modular device to acquire biopotentials

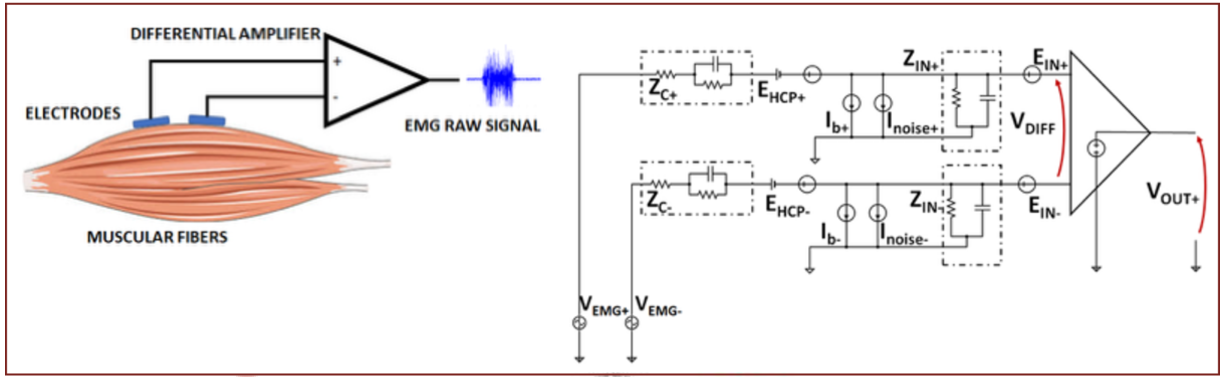
EMG Signal

- EMG signal measures the electrical activity generated by motor units in muscles
- **Motor Unit** (MU) → motor neuron and the muscle fibers it innervates
- **Motor Unit Action potentials** (MUAPs) → the electrical stimulus propagating through the muscular cells



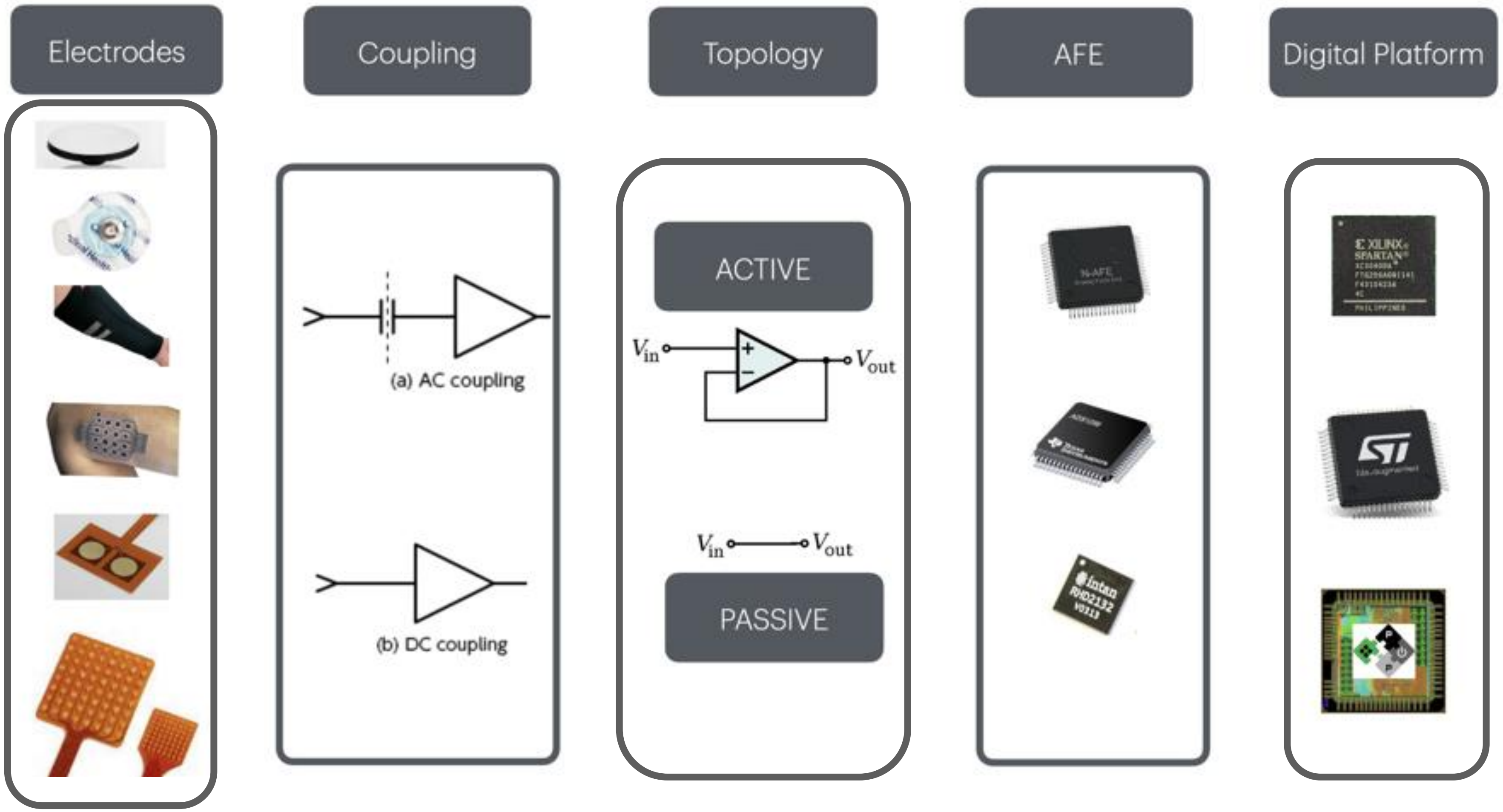
- Wide bandwidth content 20-2kHz
- Low Spatial resolution
  - Area of the sensors
  - Integrating effects of the skin

MEASURING EMG



EMG noise sources:
- Crosstalk
- Electrode-Skin interface Variability
- Perspiration

Architecture and connection schemes



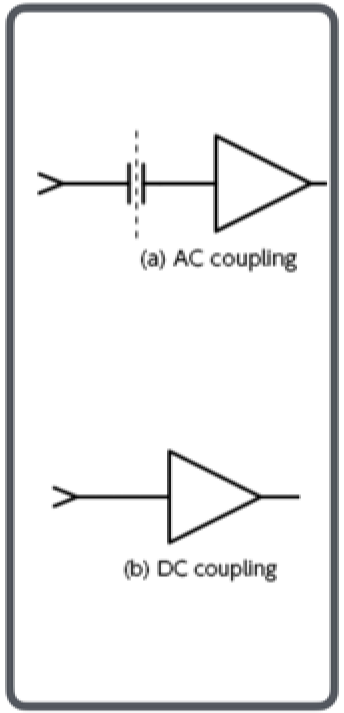
Electrodes

Electrodes

- Dry
  - No need for skin preparation
  - Motion Artifacts
- Wet
  - Not ideal for long term monitoring
  - High contact impedance
- Textile
  - Unobtrusive
  - Low contact impedance
- Skin printed
  - Custom design
  - Good contact impedance
  - Low reliability
- Capacitive
  - No direct contact of the electrode
  - Motion Artifacts
- High density
  - Ideal for neurophysiological investigation
  - Large area

Signal coupling

Coupling



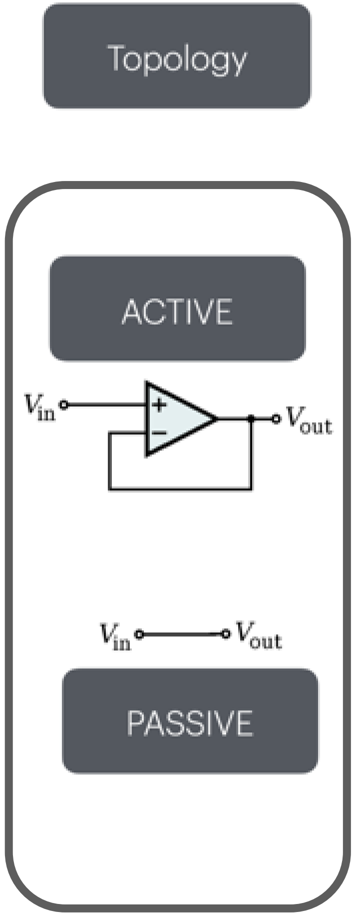
AC coupling removes the DC offset by using a decoupling cap.

- Signal normalized to a mean of zero.
- May unbalance the common-mode input impedance, degrading the CMRR value

DC coupling allows AC and DC components to pass through

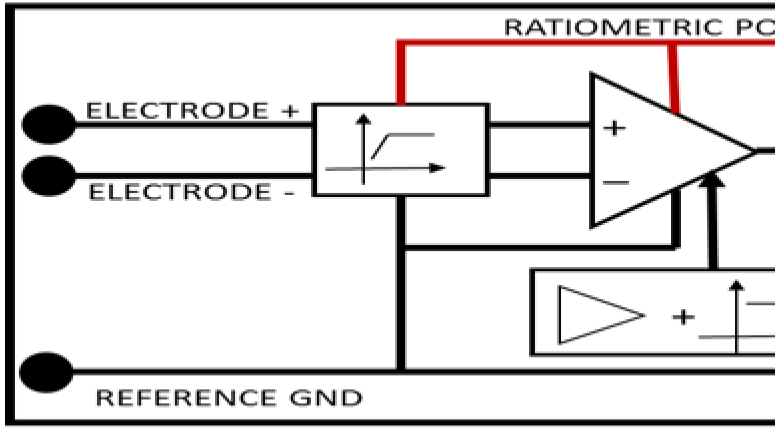
- Signal drifts → larger dynamic range (hgher power consumption).
- Higher CMRR value → no phase distortion

Active-passive sensors



Active sensors : pre-amplified electrodes

- A preamplification stage ensures higher impedance
- Reduces PLI noise



Passive Sensors : Direct connection with the ADC

- A direct connection grants a simpler design.
- Last generation AFEs feature ultra low noise

Analog Front-End

AD7177-2

- 4channles **32-bit delta-sigma.**
- Power consumption (40mW ADC)
- Programmable data rates up **to 250 kSPS**
- Good noise performance for accurate signal acquisition (2 µVPP@150 Hz, CMRR –116 dB)

ADS1298

- 8 channles 24-bit delta-sigma.
- **Low Power (0.7mW x channel)**
- Programmable data rates up to 32 kSPS
- Good noise performance for accurate signal acquisition (4 μV_{PP}@150 Hz, CMRR –115 dB).

RHD2032

- 32 channles 16-bit delta-sigma.
- **Low Power (5uW x channel)**
- Programmable data rates up to 30 kSPS
- Excellent noise performance for neural recording (2.4 µV RMS @(0.1 Hz - 10 kHz)., CMRR –90 dB)..

Digital Platform

The digital processing of the biopotentials can be executed on

- **commercial low-power / high performance programmable systems**
- **FPGAs**

- **Custom ICs**

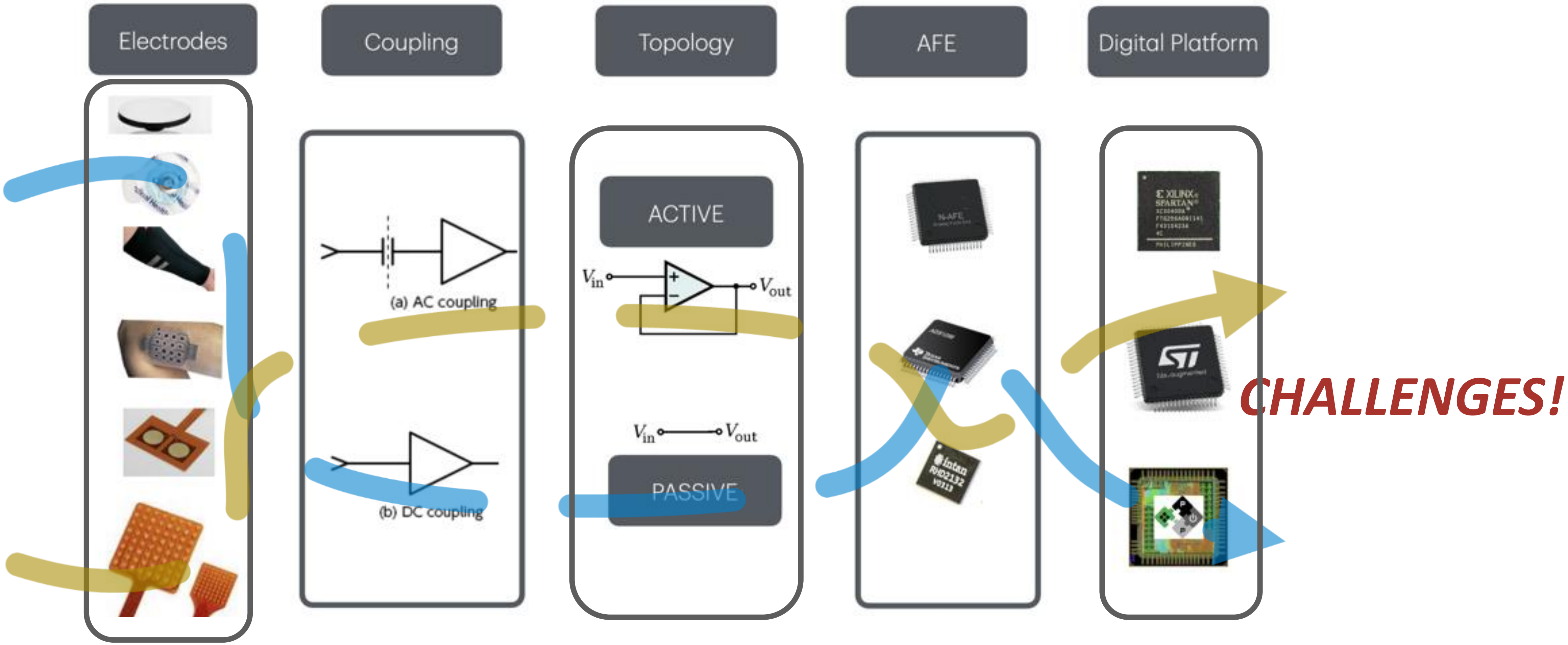
Digital Platform

High end FPGA

Microcontrollers

PULP / ASICS

Where do we stand ?



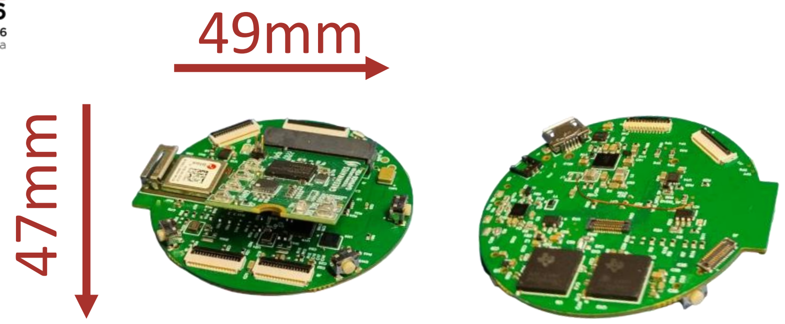
GAPwatch: a modular wristband-armband wearable computing platform

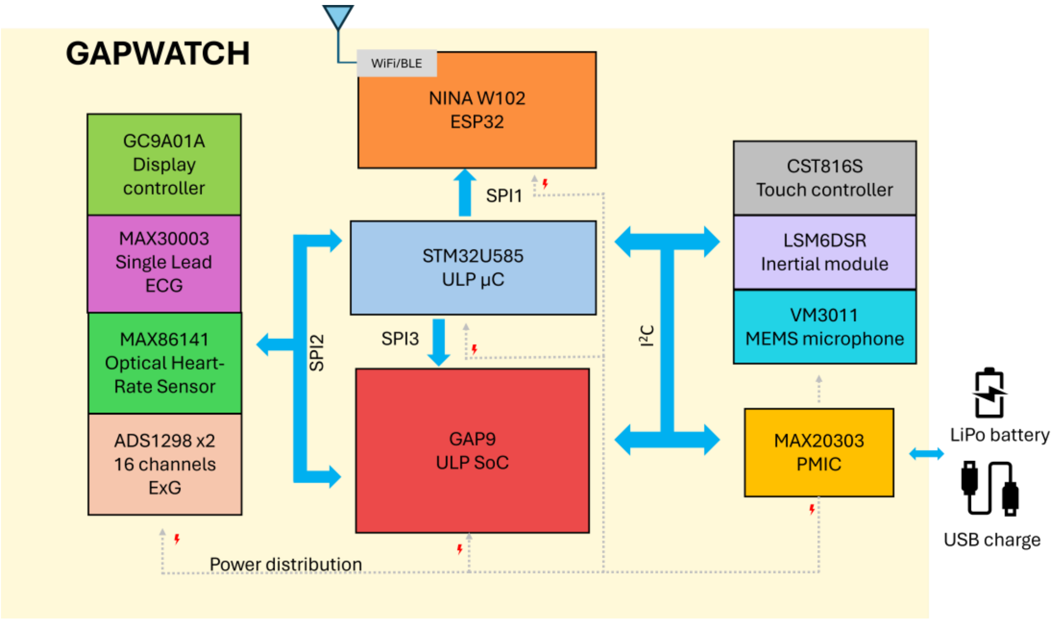
- PULP-based computing platform: **GAP9**
  - TOPS capabilities, 10 RISC-V cores, 128 kB L1 memory, 1.5 MB RAM, 370 MHz operation (state-of-the-art performance for tinyML)
- ESP32 WiFI + BLE connectivity
- 16 ExG channels AFE based on ADS1298 for biopotential measurement
- 9 Axis UMU
- EDA-PPG-ECG acquisition IC
- Microphone

GAPWatch: Main Components

- **Compute:**
  - GAP9 SoC
  - µC (STM32U585)
- **Sensors:**
  - **PPG** dual channel (MAX86140)
  - **ECG** single lead (MAX3003)
  - 16 channels **ExG** (two ADS1298)
  - 3D ACC (LSM6DSX)
  - Expansion flex connectors
- **Radio:**
  - **BLE + WiFi** (ESP32)
- **UI:**
  - 240x240 display with touch interface

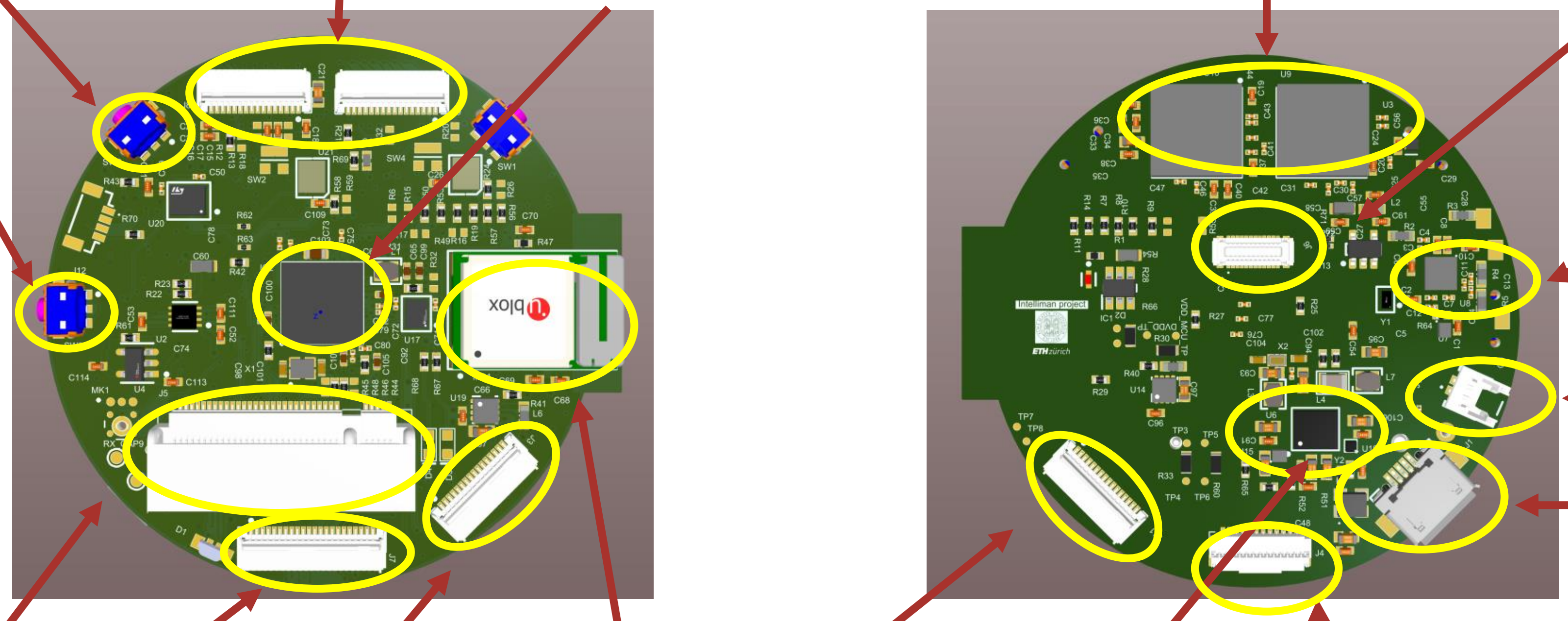
GAPWatch: System Diagram



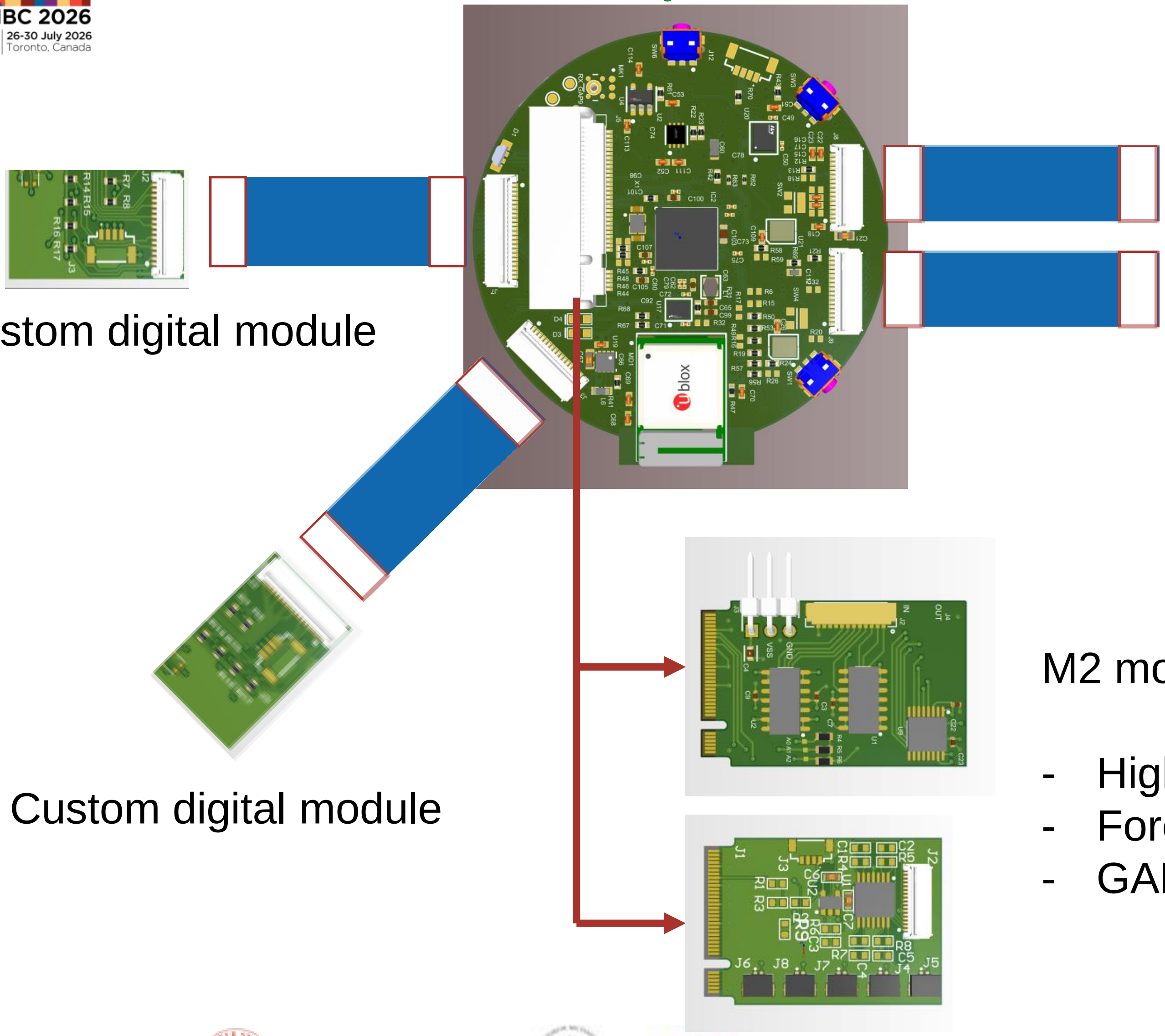


- **Data Flow**
  - STM32 microcontroller acts as the central gateway, managing all data routing so the GAP9
- **Segmented SPI Topology:**
  - Isolation of the communication lines: µC - GAP9, µC - Radio. µC - Sensors
- **Centralized PMIC:**
  - The MAX20303 handles all battery management and generates the main digital power rails.
  - Separate 3.3V rail using low-noise LDOs for analog

GAPWATCH: Base Board – Connectors

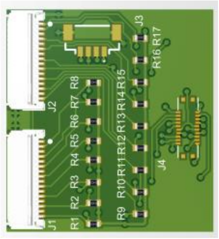


GAPWATCH: Expansion boards and connectors



Custom digital module

Custom digital module



Analog inputs

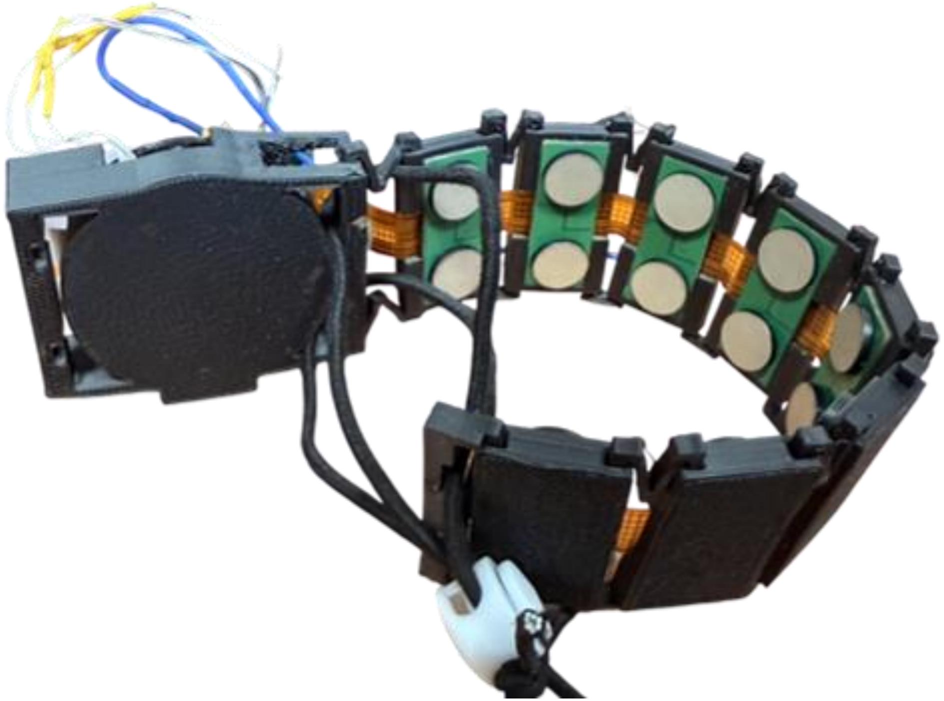
GAPwatch platform is highly configurable:

- ZIFF connectors with analog inputs
- M2 connector

M2 modules:

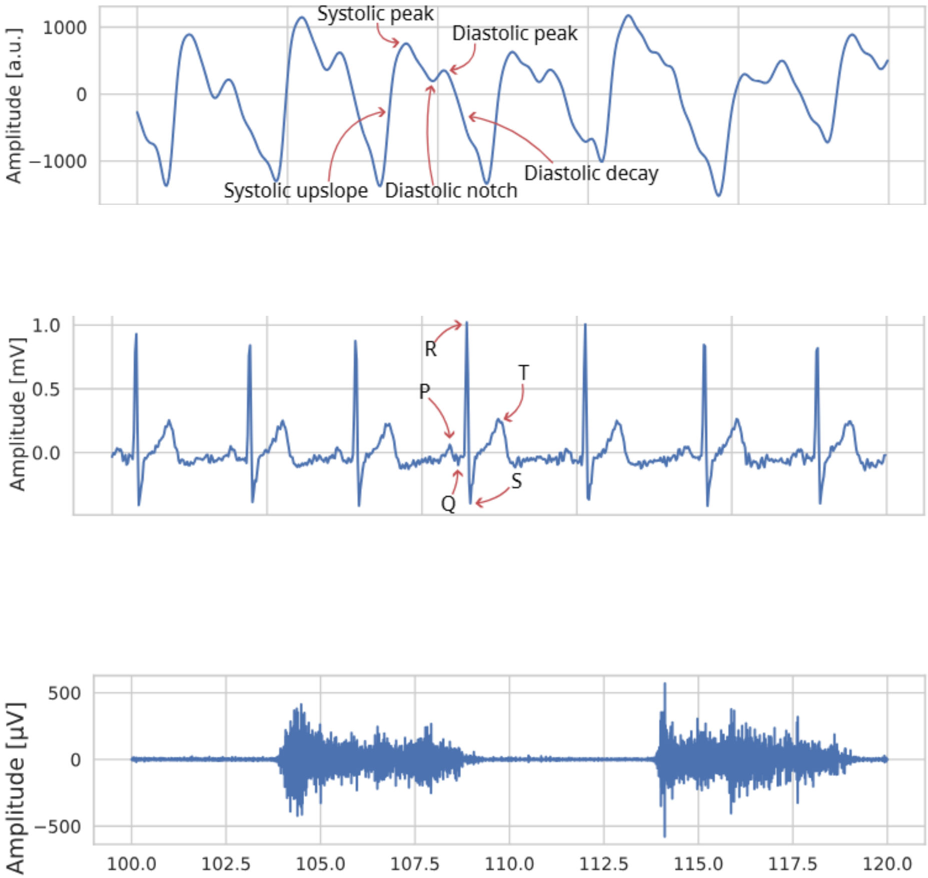
- High density EMG
- Force sensors
- GAPMOD board

sEMG Armband



- **Adaptive & Ergonomic Mechanics**
  - Fully 3D-Printed TPU Structure
  - "Accordion-Style" Segments
- **Active Sensor Nodes**
  - SoftPulse™ Dry Electrodes: Every case houses two Datwyler dry electrodes
  - Local Amplification: each node features a PCB with a unit-gain, low-noise amplifier.
- **Routing & Integration**
  - Flex-PCB Backbone: A PCB collects signals from all local boards
  - 16-Channel Monopolar Montage: Feeds into the smartwatch’s dual ADS1298 front-ends (24-bit ADC).
- **Streaming capabilities:**
  - Possibility to stream 16 chs @ 4ksps using WiFi
  - ~2hrs of continuous streaming (250mAh battery)

Experimental use case



- **Photoplethysmography (PPG)**
  - Origin: An optical technique using LEDs and photodiodes to measure blood volume changes
  - Key Uses: Continuous Heart Rate (HR) and SpO2 monitoring
- **Electrocardiography (ECG)**
  - Origin: Captures the electrical potential of the heart muscle across the skin.
  - Key Uses: Clinical-grade cardiovascular diagnostics, precise Heart Rate Variability (HRV) analysis.
- **Surface Electromyography (sEMG)**
  - Origin: Non-invasive recording of the biopotentials produced by skeletal muscle fibers during contraction.
  - Key Uses: Muscle fatigue tracking and advanced Human-Machine Interfaces (HMI)

Onboard Processing for Heart Rate (HR) monitoring

Challenge: Extracting accurate Heart Rate (HR) from PPG corrupted by motion artifacts

Limitation: Classical methods fail to obtain robust HR estimation under heavy motion artifacts

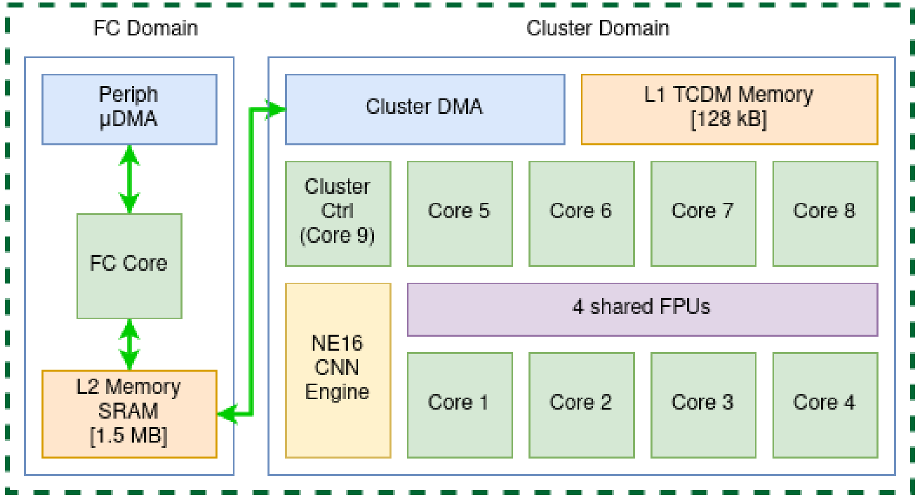
Proposed Solution: Using a lightweight Temporal Convolutional Network (TEMPONet) on a combination of PPG and 3D ACC data

Deployment: Deploy the network directly on-board the GAPWatch, exploiting its local edge computation.

Output: Stream out the final HR estimation using the BLE link.

GAP9 SoC and deployment

GAP9 SoC



- **PULP-based SoC**
- **Single-core RISC-V controller**
- **Multi-Core RISC-V Cluster**
- **NE16 AI Accelerator**

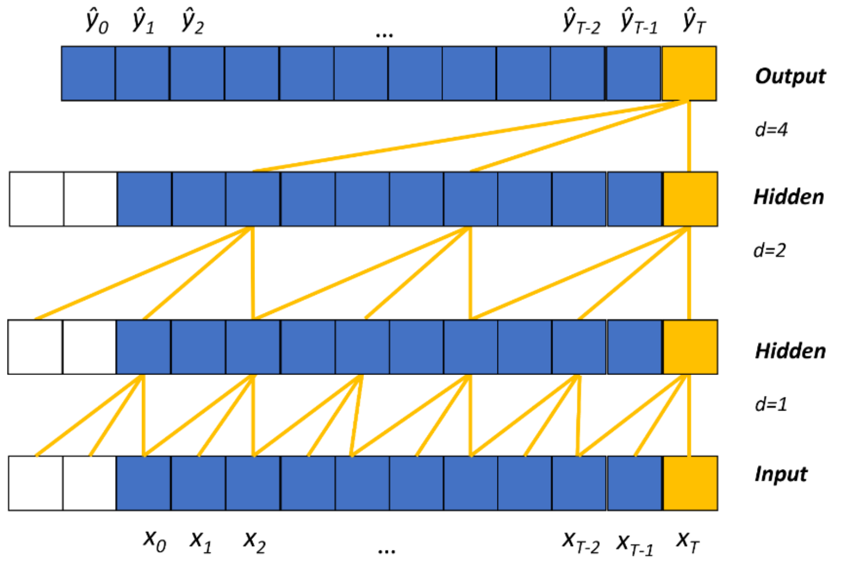
Deployment steps

ONNX

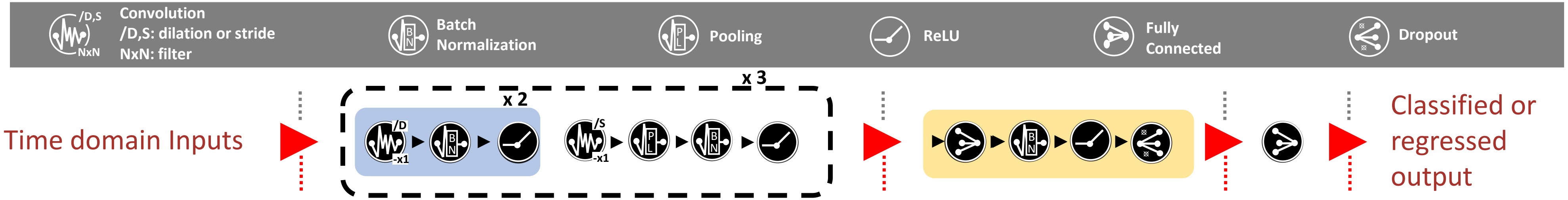
Trained model → Optional Post training quantization → NNTool + Autotiler → C code of the network

Temporal Convolutional Networks (TCNs)

- **TCNs are a specialized subclass of one-dimensional CNN that:**
  - Ensure causal convolution
  - Feature dilated convolution
  - Have an exponential growth of the receptive field with the number of layers
  - Cover long-range temporal dependencies

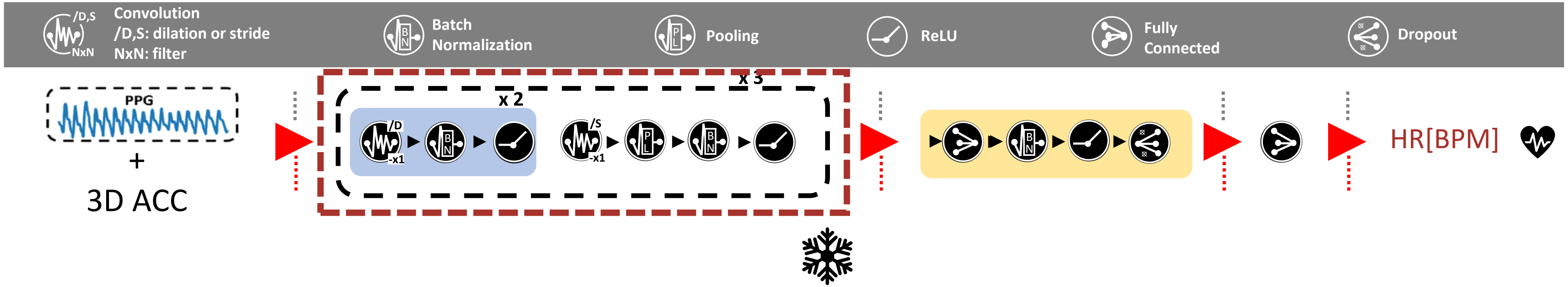


TEMPONet Architecture



- **Architectural Foundation**
  - Developed for sEMG hand-kinematics.
  - Acts as a specialized feature extractor, learning both short- and long-range temporal dependencies
- **The Feature Extractor**
  - Progressive Receptive Field: increasing dilation factors
  - Temporal Downsampling: larger kernels with strides
- **Lightweight Classification/Regression Head**
  - Tiny Memory Footprint: The head is constrained to two Fully Connected layers.
  - Flexible Output: Classification or Regression

Onboard Processing for HR Regression



Method

- Lightweight version of TEMPONet
- PPG + 3D ACC: 8s window with 2s step
- **Custom dataset 4 subjects, ~48 min**
- Synch ECG for HR Ground truth

Pre-Training

- Initial training performed on the public PPG Dalia[3] dataset to learn robust feature representations.

Fine-Tuning Strategy on custom dataset:

- Frozen convolutional blocks (first two layers); only the third block and regression MLP were fine-tuned

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Experimental Results

Deployment:

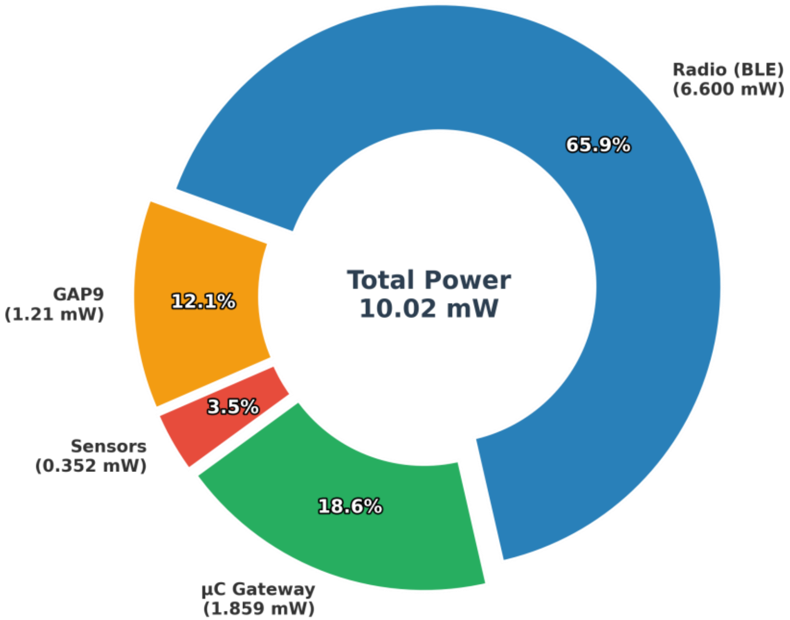
- Deployed on GAP9 using 8-bit quantization
- **162k** params
- Inference time of just **2.83ms**
- **58µJ** per inference

Accuracy:

- MAE of **3.18** ± 0.55 bpm for the finetuned network
- 2x better than frozen net

Power budget:

- Average power of the system of 10mW, >92-hours of battery life
- 13x less power than transmitting raw signals



Thank you for your attention!