PROS: an Efficient Pattern-dRiven cOmpressive Sensing Framework for Low-Power Biopotential-based Wearables with On-chip Intelligence

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Motivation

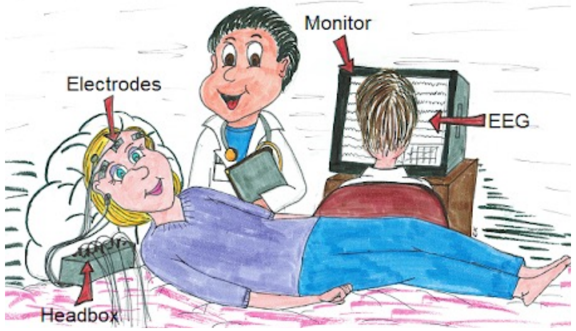
What can we enable w/ <u>40X high-fidelity biosignal compression</u> on wearables?

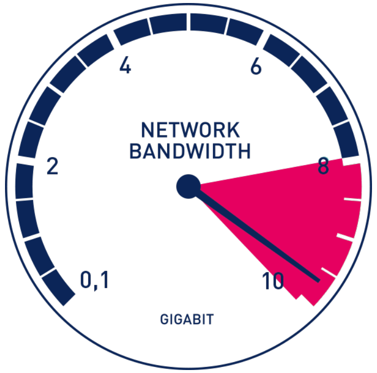
Prevent fatalities!

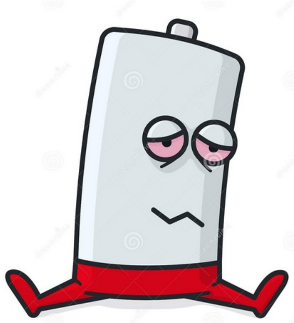
Enhance usability!

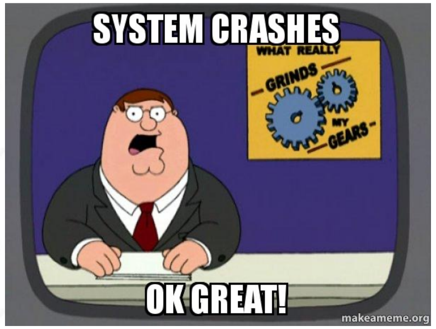
The problem

Many healthcare biosignal-based applications are not practical for wearables!









Long-term, high-fidelity monitoring

Weeks/Days not hours!

High data rate

Communication is energy heavy!

Low-latency response

Slow responses could be fatal!

Small battery, resource-constrained devices

MHz CPU, KB Memory!

The conventional trade-off

Signal Quality

VS.

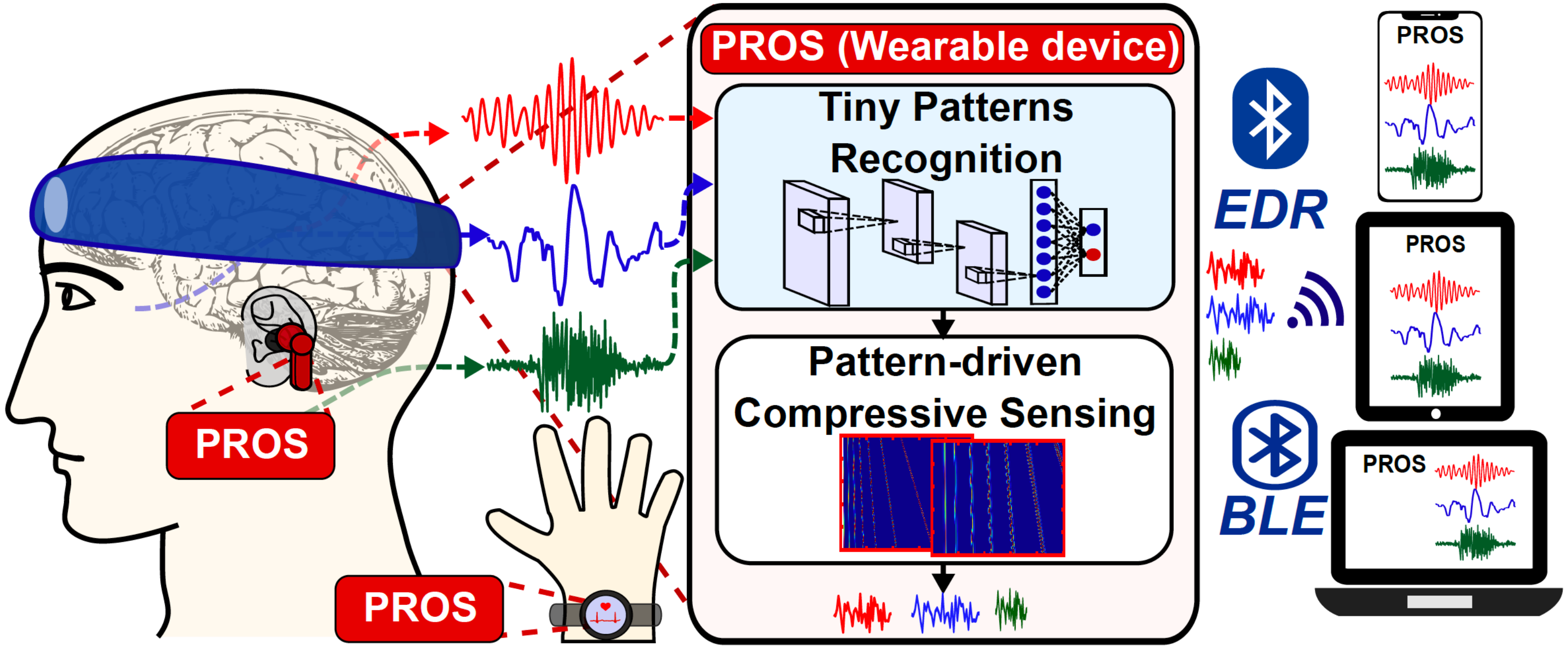
Battery Life

Medical Biosignal Monitoring
Brain/Eyes/Muscle: 10-20x1024Hz.
Battery life: >24h, w/ a big bag of batteries
Need constant monitoring by technicians.

Embrace2 Wearable
Battery life: 48h
Sweat: 4Hz (vs 512Hz in diagnostic)
Motion: 3x32Hz, Temp.: 1Hz.
Real-time alerts through a mobile app.

A new solution is needed to overcome this trade-off!

Our proposed Pattern-dRiven cOmpressive Sensing (PROS) system

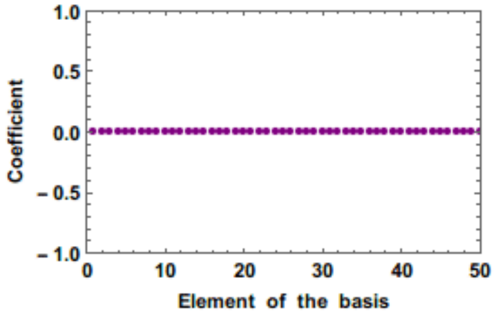


- Long battery life
- High fidelity biosignals
- Low-latency responses
- Computational efficiency

Observations

❑ #1: Biosignal events are sparse!

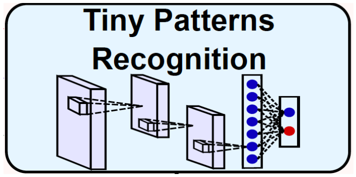
❑ #2: Biosignals are (potentially) sparse!



Exploiting event and signal sparsity -> significant streaming data reduction

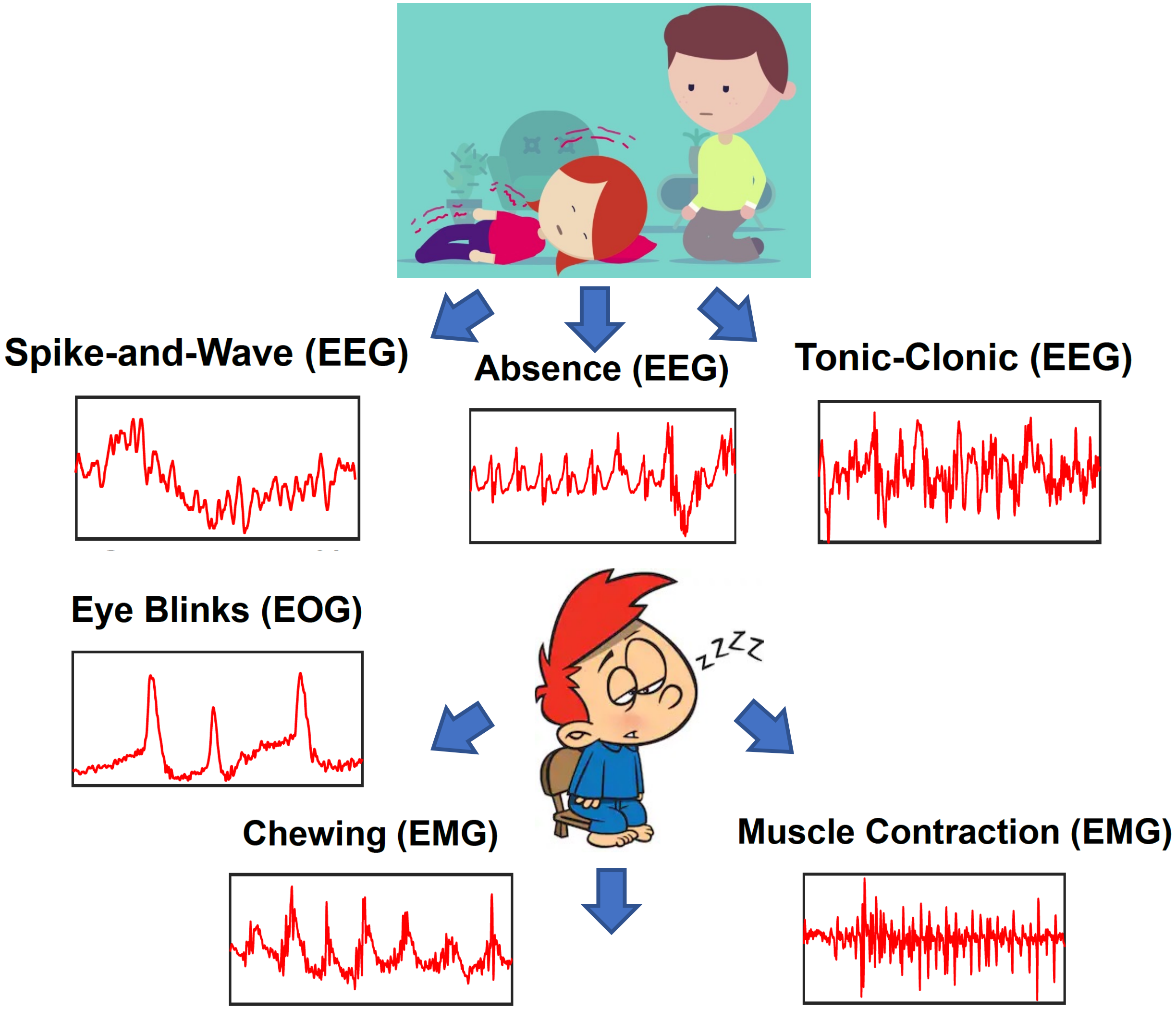
❑ #3: However, developed algorithms need to be efficient!

Challenge #1: How to detect biosignal events efficiently on wearables? (1/2)

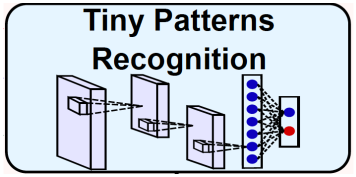


- **Detection of biosignal events on wearables is challenging!**
  - **Multiple signal modalities** (e.g., EEG, EOG, EMG, etc.)
  - **Constrained hardware and energy** resources.

Complex biosignal events can be broken down into patterns of interest (PoIs)!

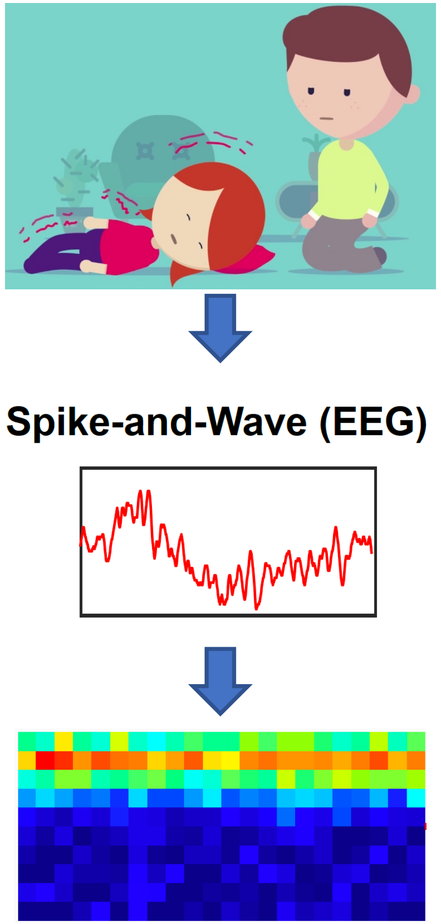


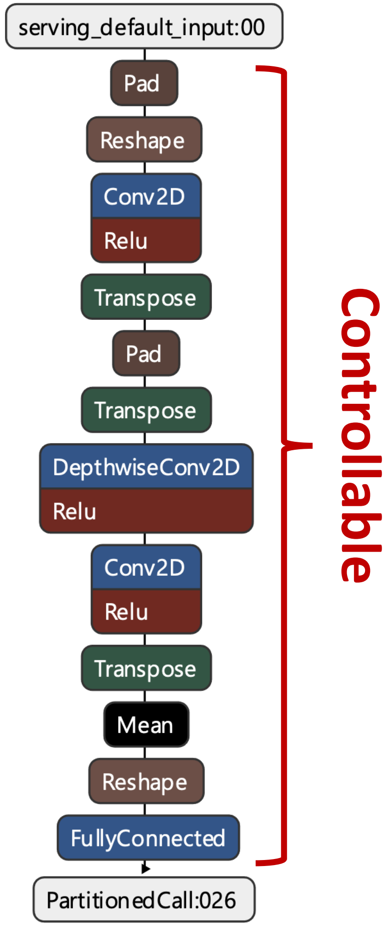
Challenge #1: How to detect biosignal PoIs efficiently on wearables? (2/2)



- **Tiny Pattern Recognition models (TinyPRs)**
  - **Each TinyPR detects one pattern.**
  - **Fine-tuned feature extraction** (MFCC).
  - **Flexible Depth-wise and Point-wise Convolution** layers.
  - **Accelerated by SIMD and DSP**.

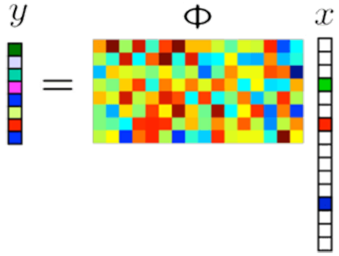
How can we push the data transmission reduction further?





Pattern probability

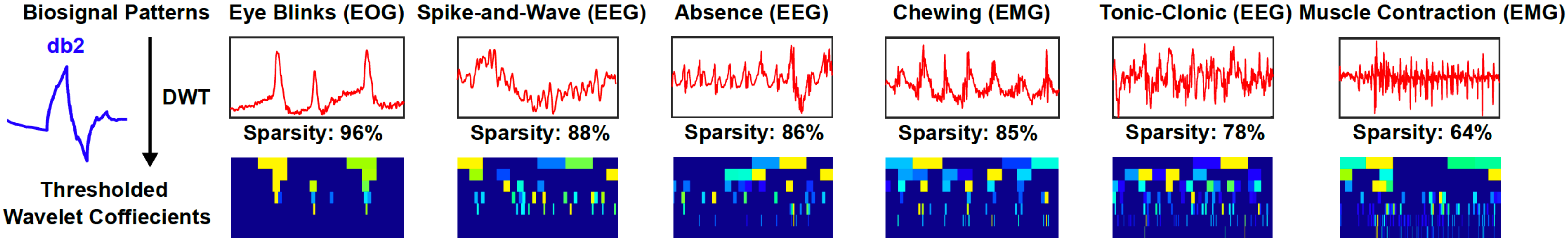
Challenge #2:How to compress the detected PoIs? (1/2)



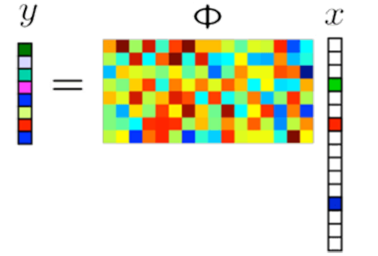
- Biosignals are potentially sparse in time-frequency domains (wavelets, Gabor, etc.), but…
  - **Large variations** among channels and trails. -> **sub-optimal compression!**
  - **A universal optimal sparse domain might not exist.**

Optimal domains for individual biosignal patterns!

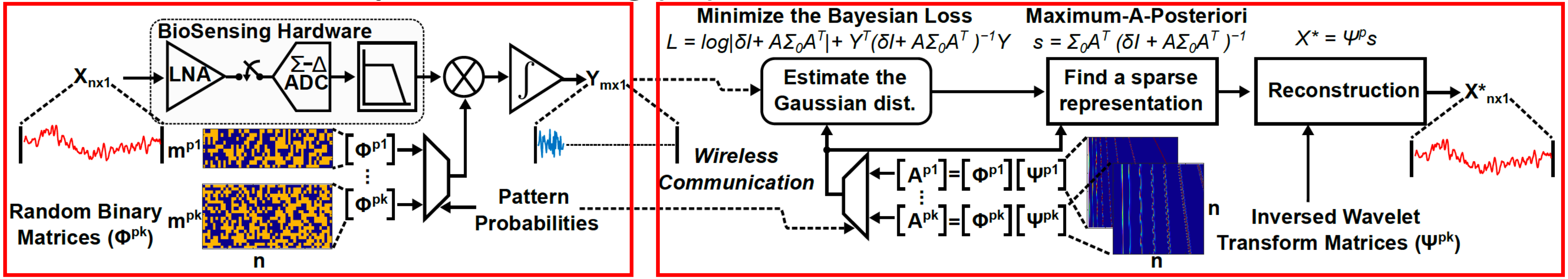
Optimal Wavelet Search Algorithm



Challenge #2:How to compress the detected PoIs? (2/2)



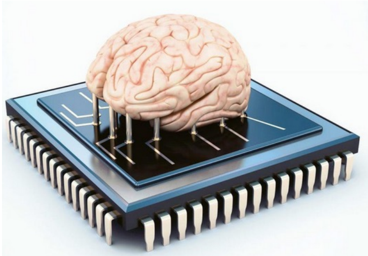
❑ Pattern-driven Compressive Sensing (CS)



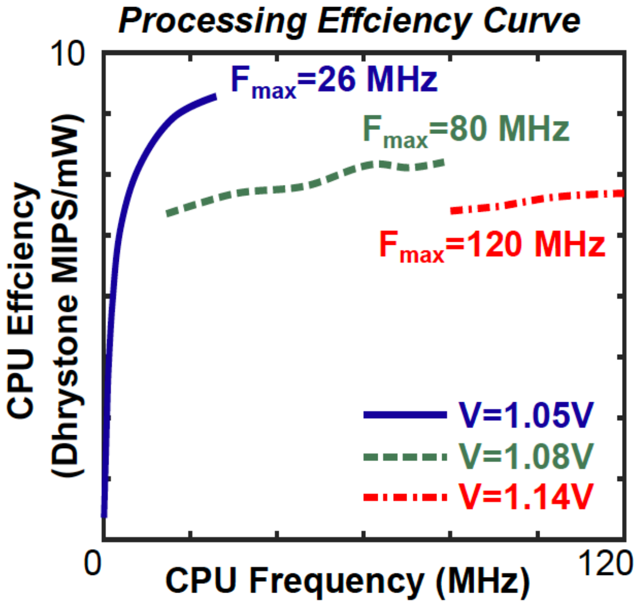
- ○ **Wearable device:**
  - **Pattern probability** from TinyPRs.
  - **Dynamic Random Binary Matrices** compressing based on the detected patterns.
- ○ **Mobile device:**
  - Biosignal reconstruction based on **Block Sparse Bayesian Learning.**
  - **Dynamic wavelet domains selection** on the fly.

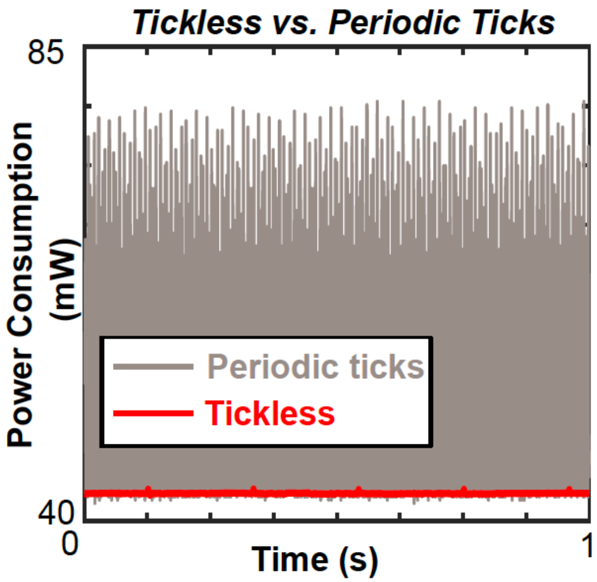
Processing efficiency?

Challenge #3: How to optimise processing efficiency? (1/1)

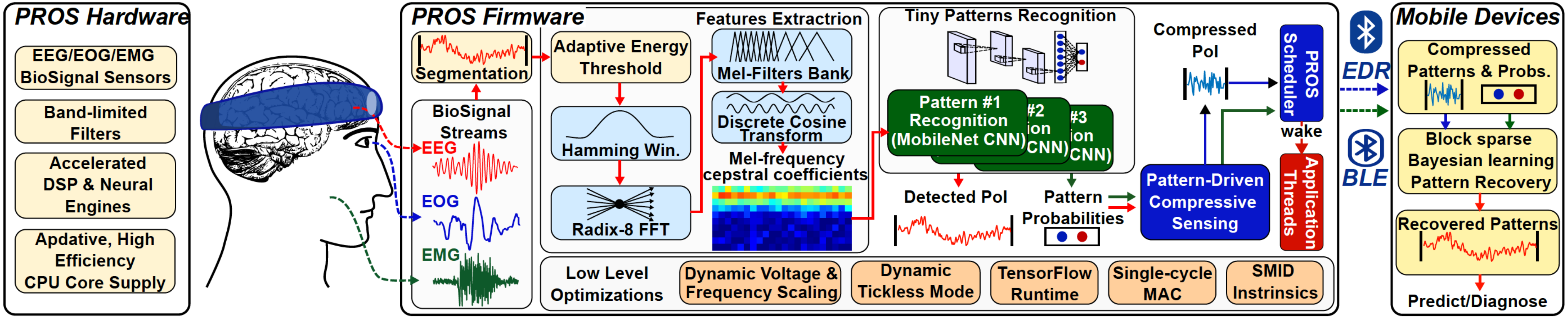


- **Dynamic Frequency and Voltage Scaling (DVFS)**
  - **Choose the optimal CPU efficiency point** based on application's requirements.
  - **↑ CPU Frequency** -> **↑ Sleep time** -> **↑ Voltage**
- **Adaptive Energy Detector**
  - Some **background signals are too obvious** for TinyPRs!
- **Tickless Kernel Mode**
  - **Eliminate periodic CPU wake-ups!**
  - Ultra-low power **interrupt-based timebase.**



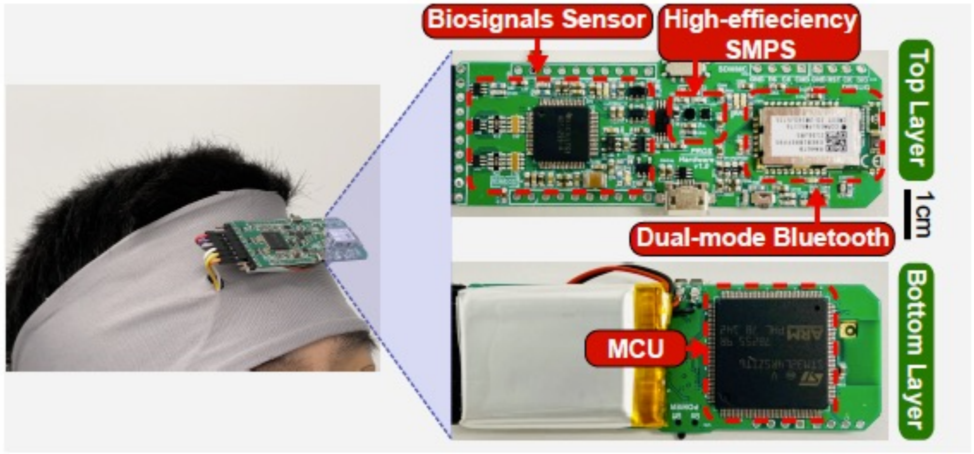


Implementation



System Overview

- **Wearable**
  - Low-power ARM MCU, 120 MHz, 1MB FLASH, 256KB RAM,
  - TinyPR pipeline,
  - Pattern-driven Compressive Sensing,
  - Hardware and low-level optimisations.
- **Mobile**
  - Surface Go, Galaxy S20,
  - Reconstruction algorithm.

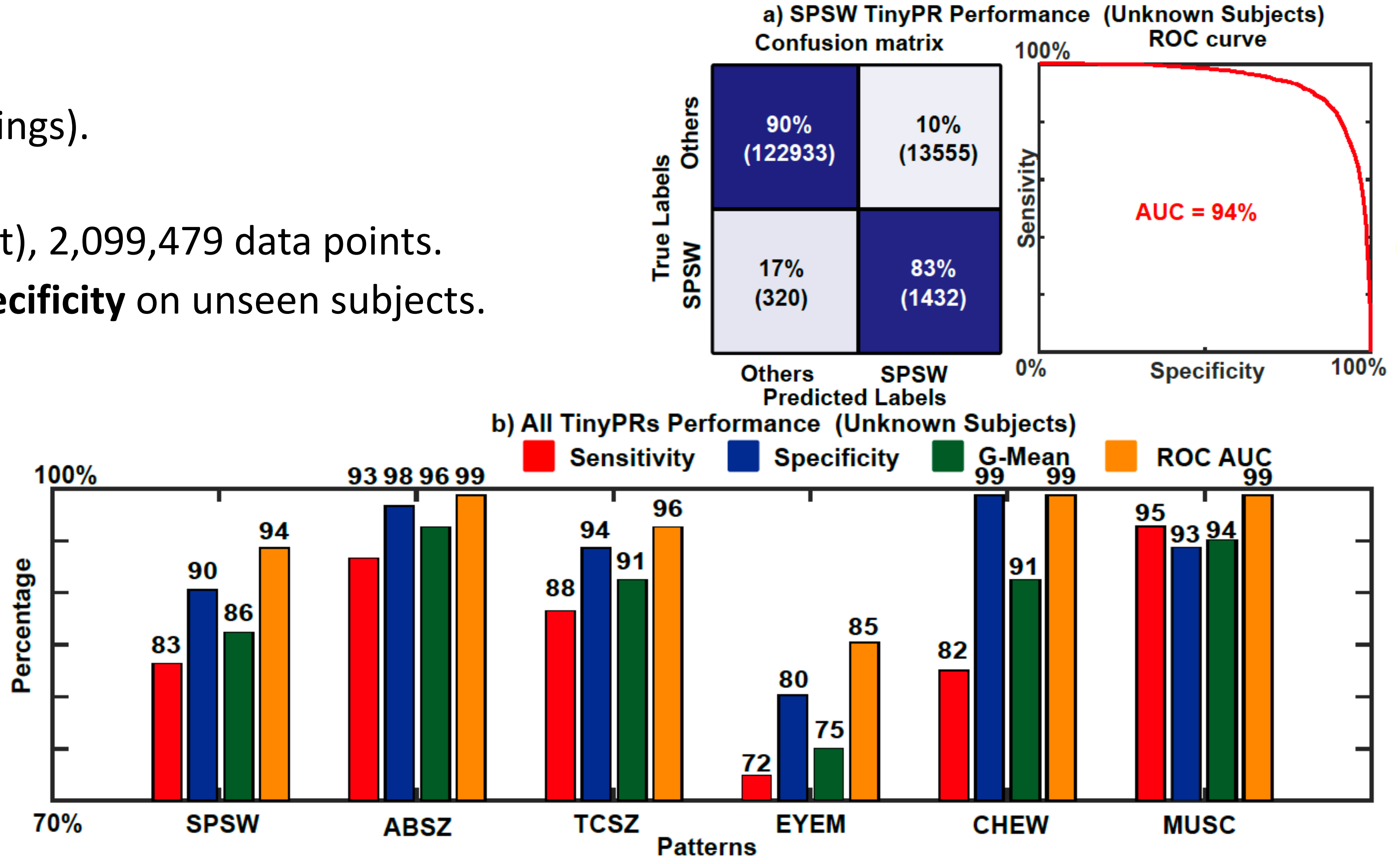


Optimised biosensing hardware

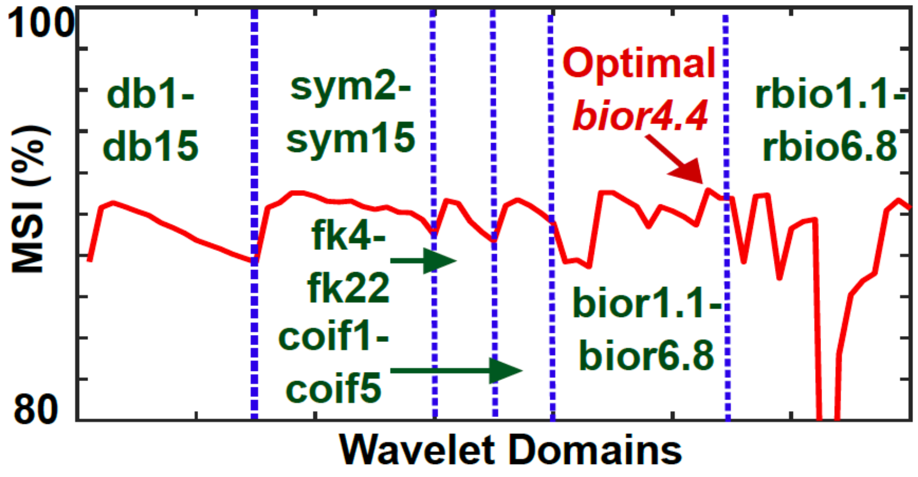
Evaluation #1 – Tiny Pattern Recognition Performance

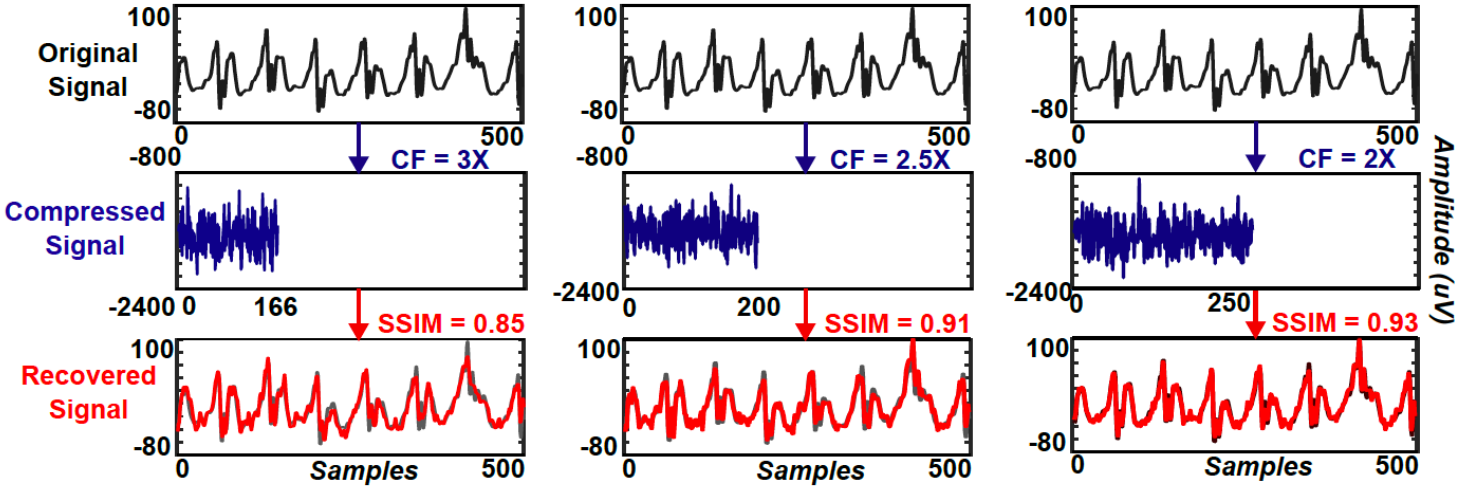
❑ TinyPR's performance:

- 2 open datasets (hospital settings).
- 6 biosignal patterns.
- 120 subjects (100 train/20 test), 2,099,479 data points.
- **75% - 96% Sensitivity and Specificity** on unseen subjects.



Evaluation #2 – Pattern-Driven Compressive Sensing Performance



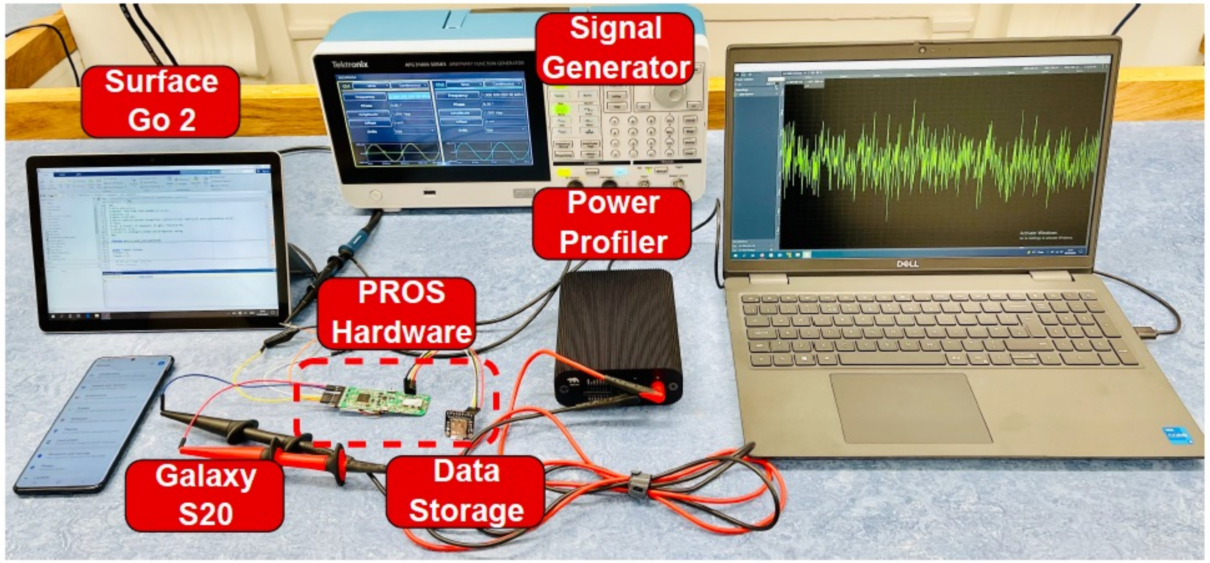


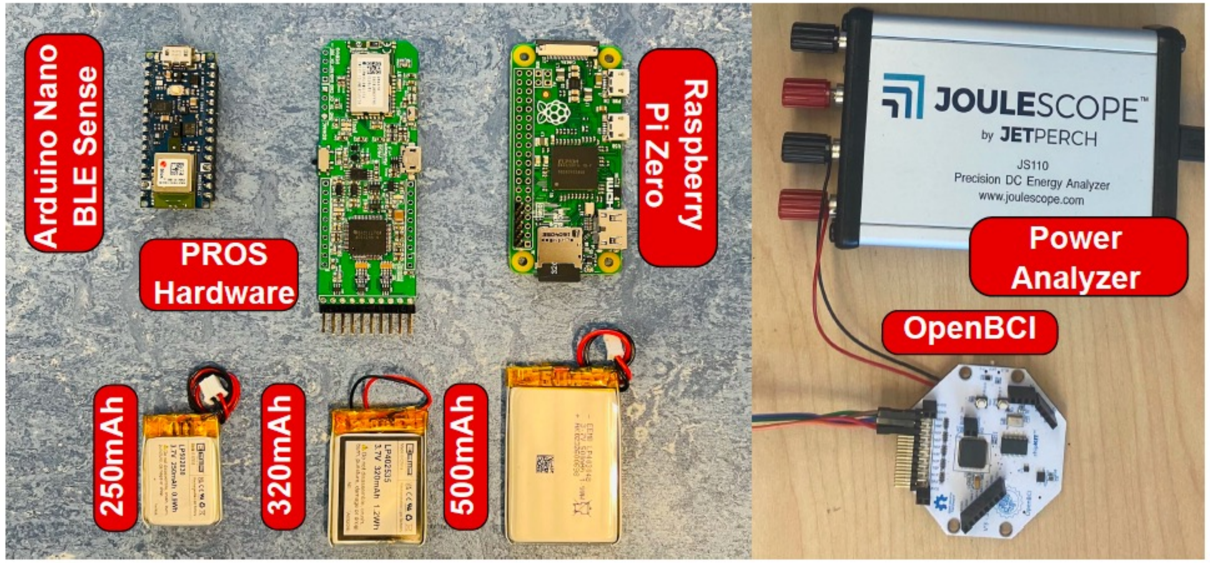
- **Optimal wavelet search**
  - **71% - 93% sparsity** for each biosignal pattern.
- **CS performance:**
  - Up to **5X compression** (CS alone)
  - Up to **40X compression** (CS + TinyPR)

Table 1: Recovery quality with different CFs.

Pattern	Wavelet Domain	MSI (%)	SSIM with different CFs (w=3s)				
			1.5X	2X	3X	4X	5X
SPSW	bior6.8	92.6	0.99	0.98	0.96	0.94	0.89
ABSZ	bior4.4	91.2	0.99	0.97	0.94	0.89	0.82
TCSZ	sym14	71.4	0.84	0.81	0.57	0.39	0.31
EYEM	sym5	89.6	0.98	0.97	0.91	0.84	0.80
CHEW	bior4.4	84.0	0.93	0.93	0.84	0.78	0.71
MUSC	sym5	79.7	0.92	0.88	0.70	0.60	0.50

Evaluation #3 – Hardware runtime performance





❑ Hardware performance

- **TinyPR**: 5KB FLASH, 30 KB RAM, 26ms (@120MHz).
- **CS**: 4-30KB FLASH, 1ms (Wearable), 50-94ms (Mobile devices)

❑ Epileptic Seizure Monitoring use case:

- **10 unseen subjects:** 277,662 data points.
- **3 patterns:** Focal, Absence, Tonic-Clonic.
- **High-fidelity:** 85% Sensitivity, 0.92 SSIM.
- **Transmission reduction:** 24X.
- **Energy improvement**: >1200%.
- 500mAh -> last the whole week.
- Able to **detect fatal tonic-clonic seizures < 32ms.**

Future work

- **Future work:**
  - **Improve pattern recognition performance.**
  - **Extending and sharing ability for various signals and multiple applications.**
  - **In-the-wild evaluations.**

- **Open-source resource:**
  - https://github.com/PROS-public. (LGPLv2 License)

Thank you for your attention!