Center for Embedded Systems
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Adaptive compressive sensing techniques for low power sensors

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Project Overview and Description

- **Project Description**
  - investigate the **need, benefits**, and **circuit techniques** to implement adaptive compressive sampling schemes in sensors with compressive sensing techniques.
- **Problem**
  - Most compressive sensing sensors assume the sparsity of sensor signals is relatively stable and hence use fixed compressive sampling schemes.
  - The sparsity of certain sensor signals may exhibit significant fluctuations. Thus, adaptive compressive sampling potentially leads to more power-efficient implementations.

Approach

- Perform system-level simulation with using realistic sensor signals (Multi-parameter Intelligent Monitoring in Intensive Care database) to study the fluctuations of signal sparsity.
- Based on system-level power models, study the potential power saving by adaptively adjusting the compressive sampling schemes.
- Develop new circuit techniques to address the challenges on implementing adaptive compressive sensing (ACS).

Project Status

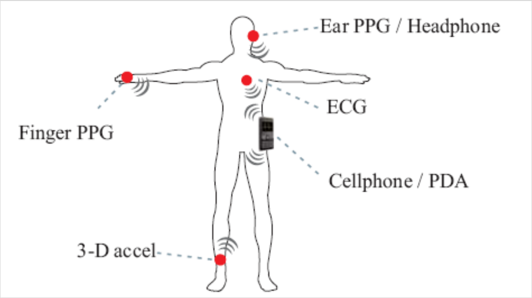
- Study of signal sparsity fluctuation is completed. It shows the validity of adaptive compressive sensing
- The investigation on potential power saving is complete. It indicates significant power can be saved by ACS
- Matlab simulation package for checking the applicability of ACS and potential power saving is available for member companies
- Current work focuses on the design of analog circuits to be used in ACS

Project Tasks/ Deliverables

	Description	Date	Status
1	Investigating the applicability of adaptive compressive sensing and demonstrating the potential power saving	8/13	Completed
2	Improve and encapsulate the matlab programs into a simulation package	10/13	completed
3	Design of analog wavelet transform circuit	03/14	On-going
4	Establishing the relation between circuit output and desirable sampling size; evaluating its effectiveness	07/14	

Executive Summary

- Compressive sensing is emerging as a new technique in ultra-low power sensor design.
- Adaptive compressive sensing can potentially result in further power saving.
- The project investigates the **need, benefits,** and **circuit techniques** to implement adaptive compressive sensing schemes
  - An interesting application area of the developed technique is in the design of biosensors that are parts of body area network and communicating with mobile devices

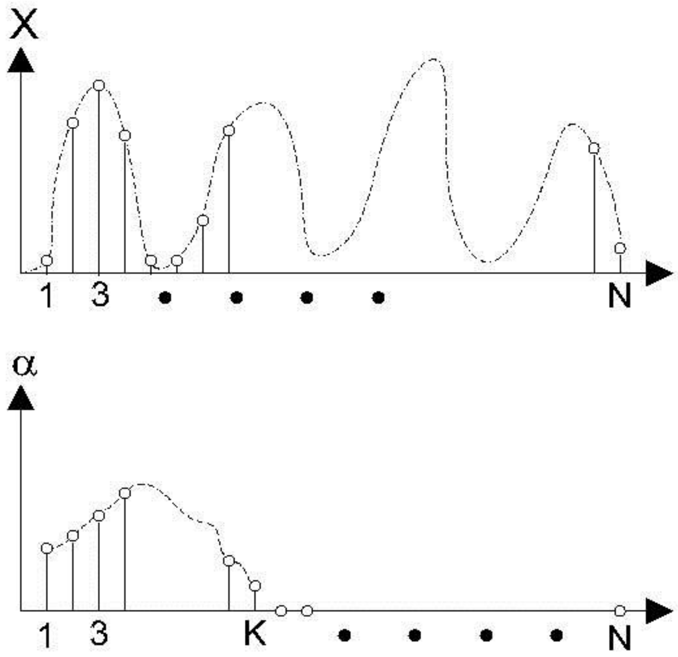


Source: Baheti, P.K.; Garudadri, H.; "An ultra-low power pulse oximeter sensor based on compressed sensing," Sixth International Workshop on Wearable and Implantable Body Sensor Networks, pp. 144-148, 2009.

Technical Detail

- **Signal sparsity**
  - Sensor signal X (X has N terms) is projected to another domain by matrix Ψ :

$$X = \Psi \cdot \alpha$$



  - The projected values is represented by vector α
  - If only K terms in α are significant and K<N, signal X has sparse representation in domain Ψ

Technical Detail

- **Incoherent sampling**
  - Sensor signal X is processed by another matrix operation (incoherent sampling)

$$Y = \Phi \cdot X$$

  - The size of Φ is N×M and Hence the size of Y is M
  - If X has a sparse representation with K significant terms in Ψ domain and Φ and Ψ are incoherent, and the minimum size of Y is:

$$M = \mathrm{O}(K \log \frac{N}{K})$$

  - If K<<N, then M<N. Thus, sensing or sending signal Y, instead of X, will lead to low-power operations

Technical Detail

- **Signal recovery**
  - Receiver solves the α values from the received Y signal by:

$$Y = \Phi \cdot \Psi \cdot \alpha$$

    - Since α has N terms and Y has only M (M<N) terms, there exists more than one solutions
    - However, the solution with the least number of significant terms in α is often the right solution. Such a solution can be searched by convex optimization techniques
  - Once α is solved, sensor signal X can be reconstructed by:

$$X = \Psi \cdot \alpha$$

Technical Detail

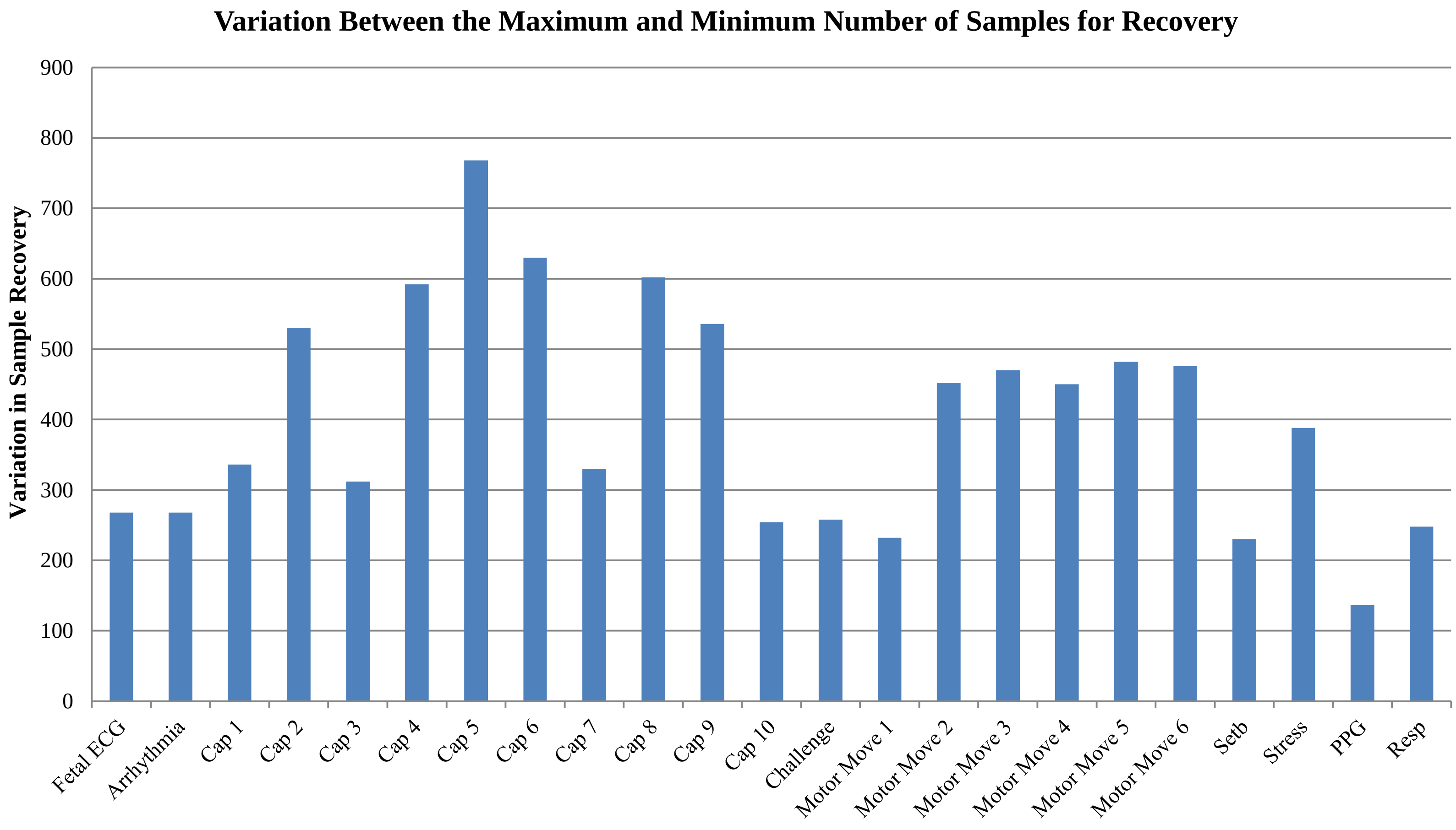
- **Investigating the fluctuations of signal sparsity**
  - Matlab/Simulink models are developed to emulate compressive sensing operations.
  - The Ψ matrices used in the models are either Gabor or wavelet matrix
  - Realistic sensor signals from MIMIC (Multi-parameter Intelligent Monitoring in Intensive Care) database are used in simulation.

Technical Detail

- **Results: Variations of signal sparisty and measurement sizes**

Signal	Block	1	2	3	4	5	6
Fetal ECG	M	357	597	449	419	329	407
	K	30	37	7	6	54	21
Cap	M	443	961	977	857	969	385
	K	114	116	97	178	116	41
Stress	M	191	209	201	187	575	193
	K	30	36	35	28	15	34
PPG	M	231	118	169	141	255	237
	K	38	41	45	42	38	36

- **Results:**

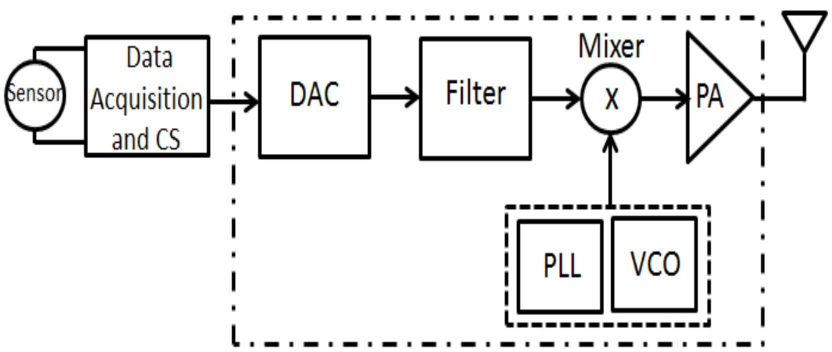


Variation Between the Maximum and Minimum Number of Samples for Recovery
Variation in Sample Recovery
900
800
700
600
500
400
300
200
100
0
Fetal ECG
Arrhythmia
Cap 1
Cap 2
Cap 3
Cap 4
Cap 5
Cap 6
Cap 7
Cap 8
Cap 9
Cap 10
Challenge
Motor Move 1
Motor Move 2
Motor Move 3
Motor Move 4
Motor Move 5
Motor Move 6
Setb
Stress
PPG
Resp

Technical Detail

- **Wireless transmitter model used in estimating power saving by ACS**

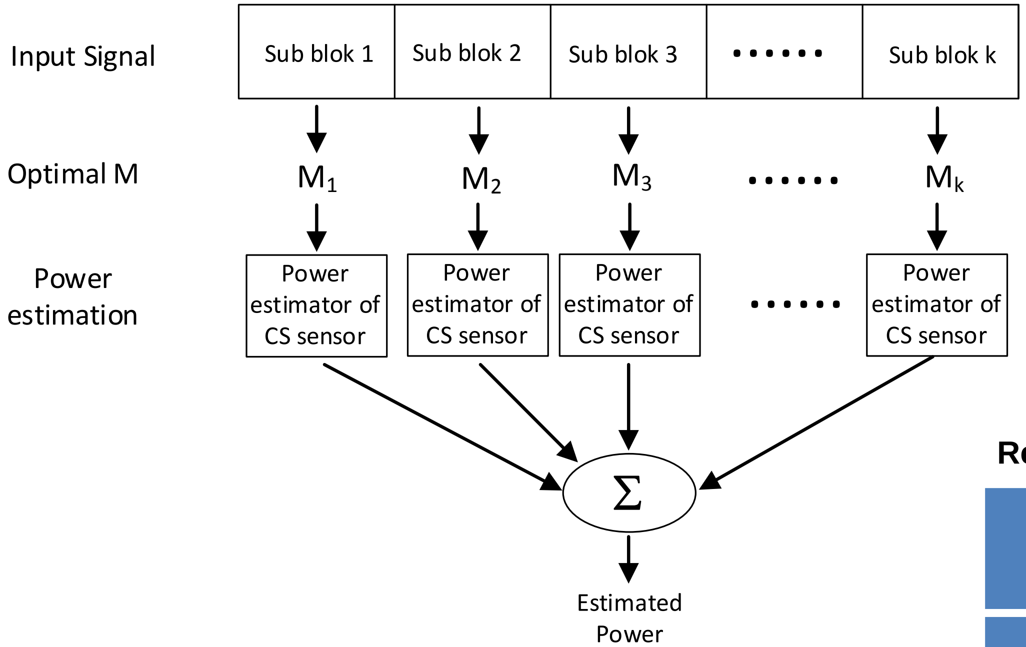
Circuit Block Diagram



Power model parameter values used in this study

Circuit Block	Circuit Parameters	Values
DAC	N	8
	C	50fF
	K	0.05
	f_conv	100KHz
Filter	fc	40KHz
	Q	5
	SNR	50dB
	η	1×10^5
Mixer	k_{mixer}	10×10^{-3}
	G	0dBm
	NF	10dBm
PLL	A_1	1.4×10^{-6}
	A_2	1.6×10^{-4}
	f_{LO}	2.4GHz
	f_{ref}	22MHz
VCO	A	2.3
	f_{osc}	2.4GHz
	L	6nH
PA	η_{PA}	28%
	P_{out}	-3dBm

- **Simulation flow and results**



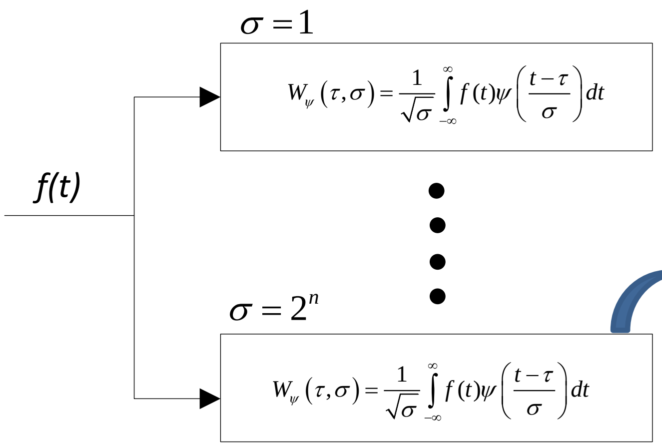
Power estimation flow

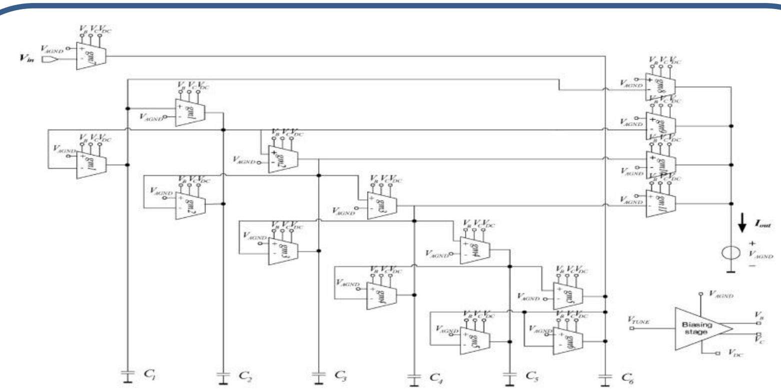
Results of the power estimation simulation

Signal	Conv. CS	ACS	Power Savings
Fetal ECG	3.08 mW	2.31 mW	25%
Cap	4.57 mW	3.75 mW	17.2%
Stress	2.98 mW	1.57 mW	47.3%
PPG	1.55 mW	1.27 mW	18.1%

Technical Detail

- **Analog wavelet transform (WT) circuit**
  - Using a group of filters which correspond to the wavelet functions with different scale σ values

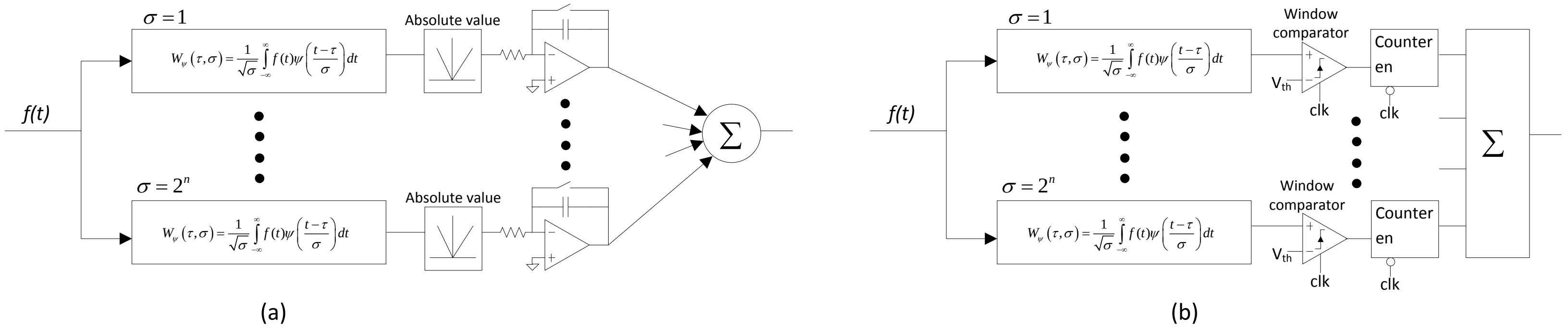




Source of Figure: J. M. H. Karel, S. A. P. Haddad, S. Hiseni, R. L. Westra, W. A. Serdijn, and R. L. M. Peeters, “Implementing Wavelets in Continuous-Time Analog Circuits With Dynamic Range Optimization,” Ieee Trans. Circuits Syst. Regul. Pap., vol. 59, no. 2, pp. 229–242, 2012

- **Difference between ours and others’ approaches** (why can we make it ultra-low power?)
  - Use circuit outputs as indicators for signal sparsity, don’t reconstruct the original signal from circuit outputs
    - Relaxed accuracy requirement; don’t have to be always on
    - Tolerance to “false positive results” (indicating signal dense, but sparse)

- **Generating sparsity indication signal**



- **Establishing the correlation:**