A Dynamically Reconfigurable ECG Analog Front-End with a 2.5× Data-Dependent Power Reduction

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BIO Sensors & Electronics

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Electrical and Computer Engineering
JACOBS SCHOOL OF ENGINEERING

Outline

- Introduction and Motivation
- Adaptive Acquisition System
- Circuit Implementation
- Measurement Results
- Conclusion

Motivation

World of IoTs and m-Health

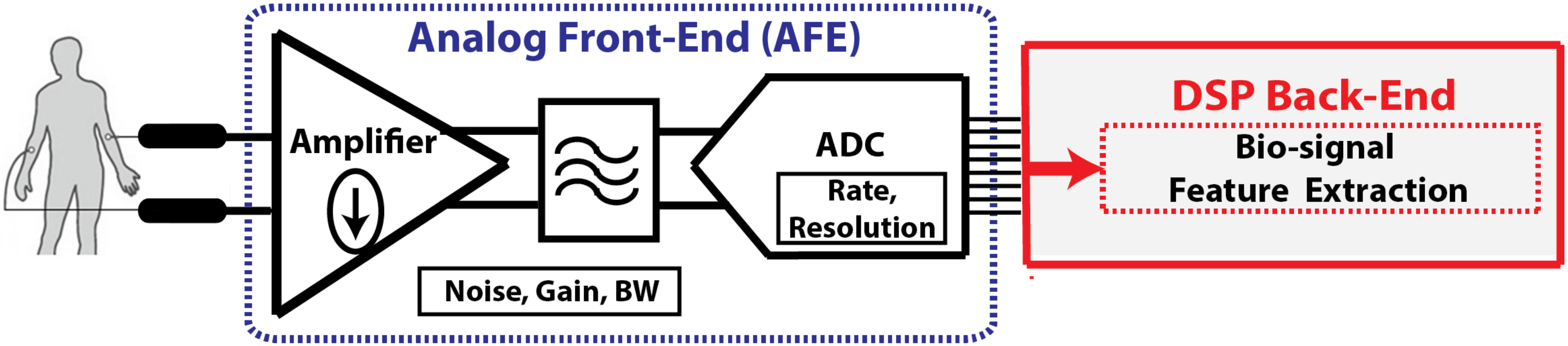
Miniaturized Wearable & Implantable Devices

❖ Automated, remote monitoring
❖ Early detection/diagnosis

Major Challenges:

- **Continuous reliable monitoring via a small integrated unit**
- **Ultra-low power interfaces with long battery life required**

Conventional ECG Sensor



Conventional low power ECG acquisition system architecture

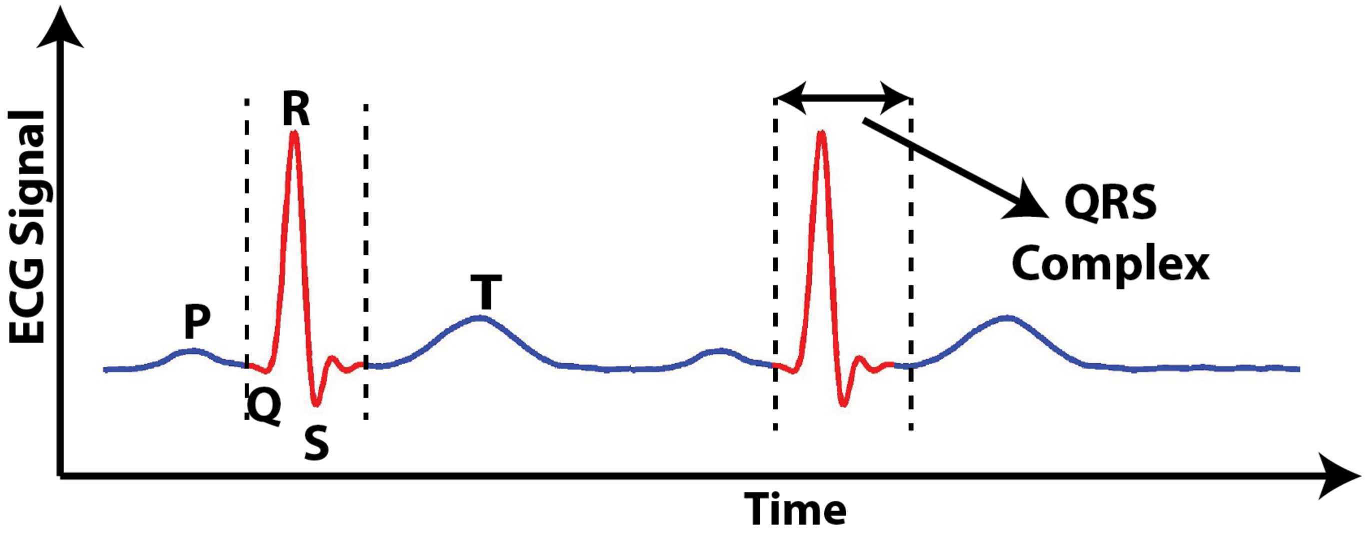
Circuit parameters:

1) Amplifier Noise
2) Amplifier Gain
3) Amplifier BW
4) ADC Resolution
5) ADC Sampling Rate

FIXED!

Overdesigned system → Unnecessarily high power

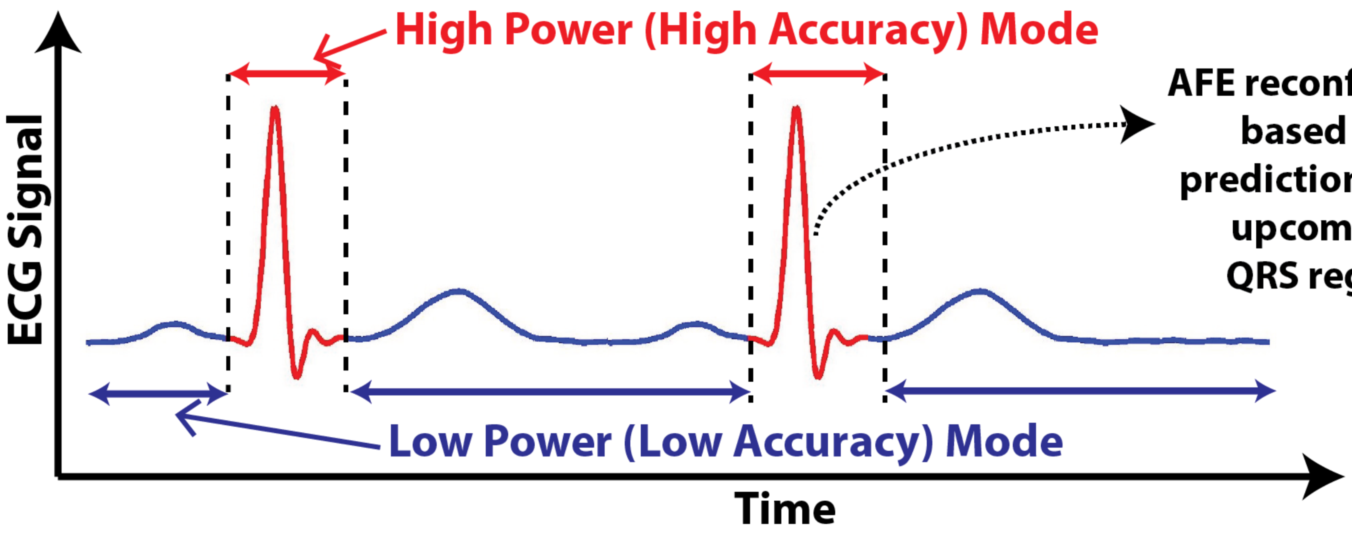
Bio Signals



Special properties of ECG

- ❑ **Low activity (QRS complex over <15% of a period)**
- ❑ **Quasi-periodicity**

Bio Signals: Data-Dependent Savings



Special properties of ECG

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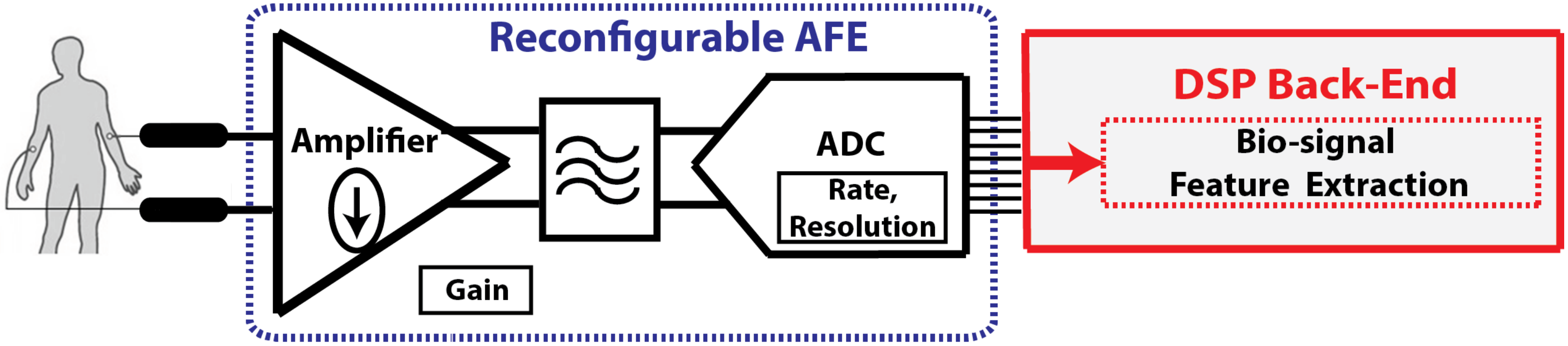
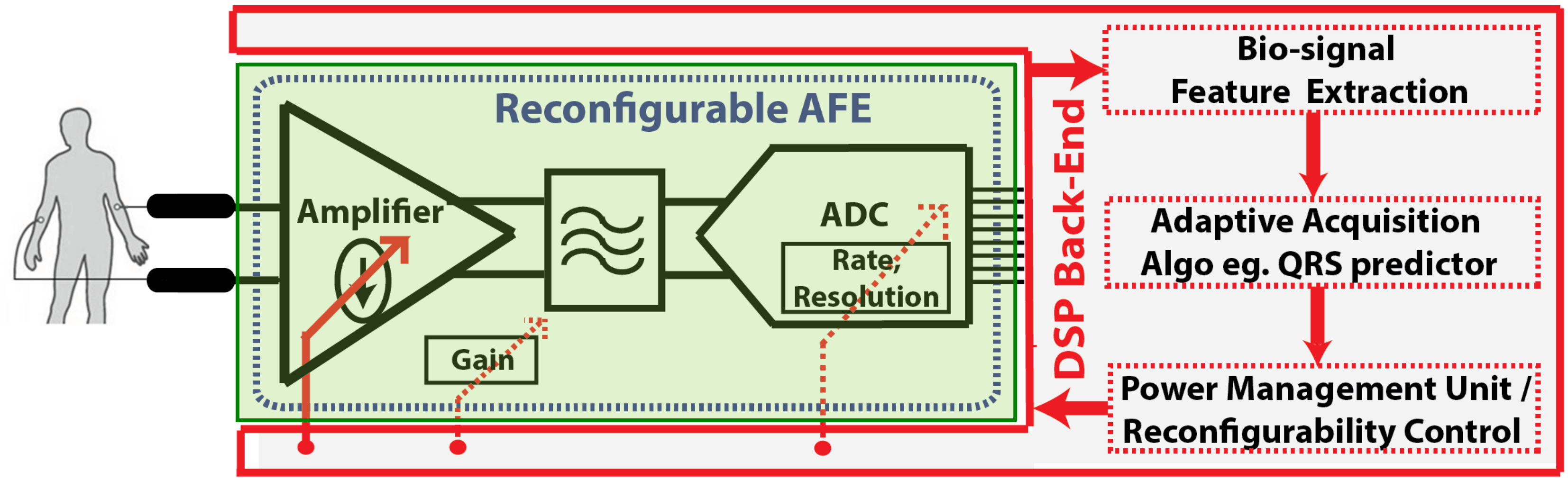
- ❑ **Quasi-periodicity**

Key Idea – Leverage inherent signal properties to adaptively reduce power

Adaptive ECG Acquisition System



Adaptive ECG Acquisition System



Digitally assisted reconfigurable AFE → Data-dependent power savings

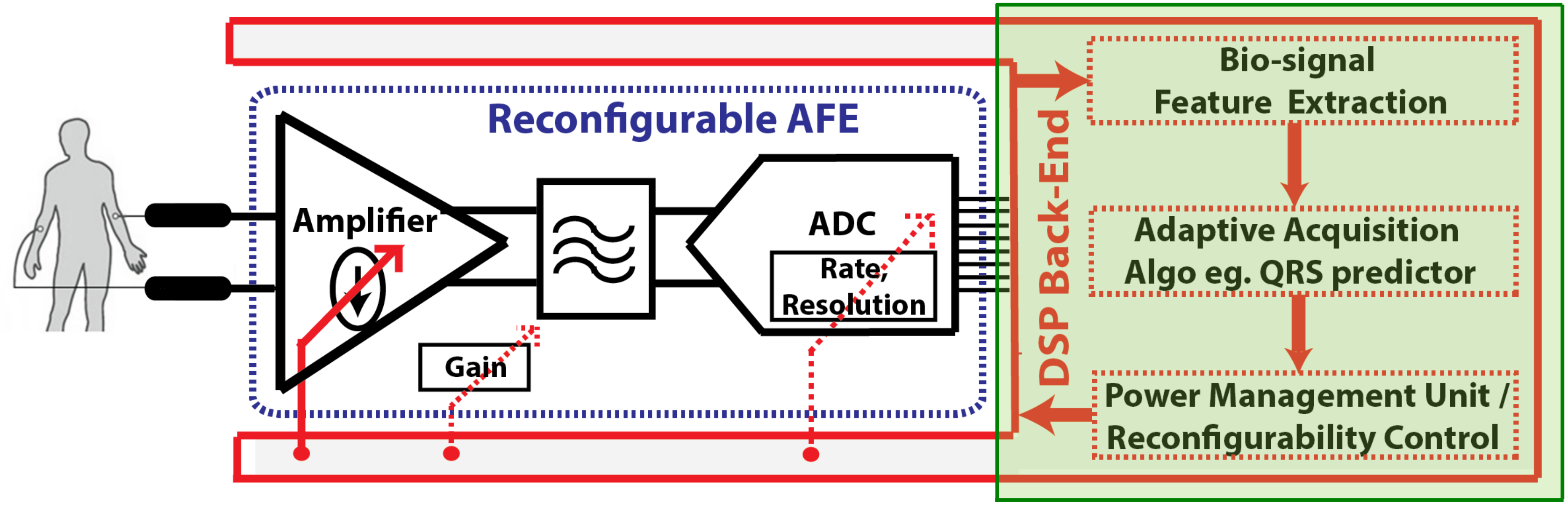
State-of-the-art low power ECG AFEs [1-2]

have $P_{AMP}/P_{ADC} \approx 10$

Focus on <u>noise-limited</u> amplifier power reduction

[1] - Yan ISSCC'14
[2] - Jeon ISSCC '14

Adaptive ECG Acquisition System

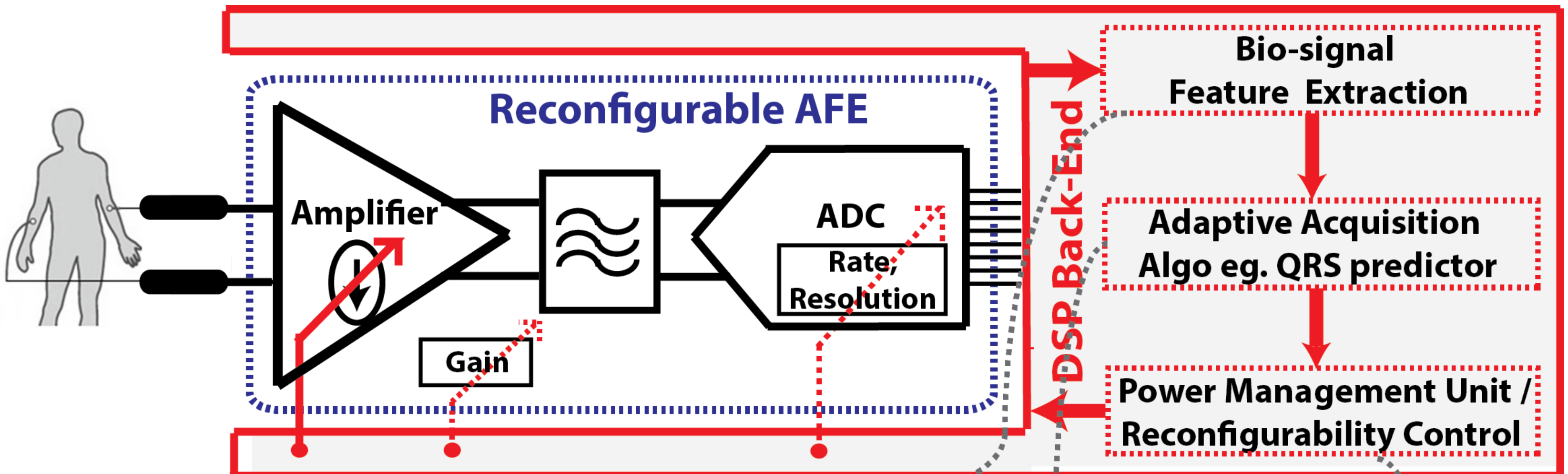


Digital Back-end → Off-chip (FPGA)

❖ State-of-the-art low power ECG feature extraction processors [3] consume 450 nW

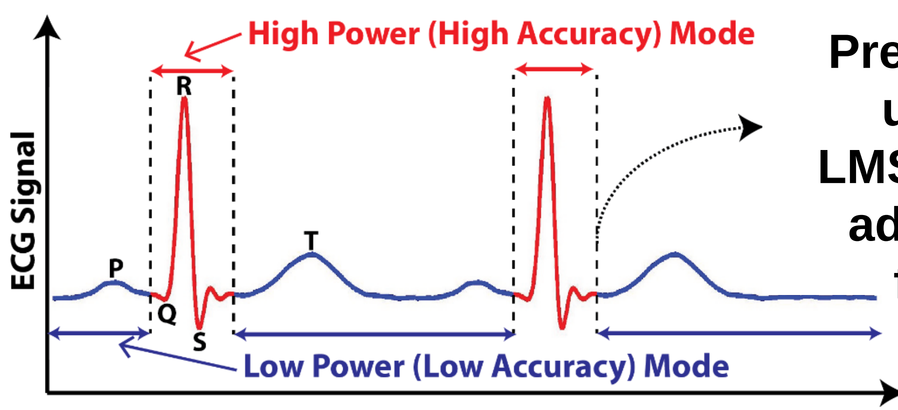
[3] - Liu JSSC'14

Adaptive ECG Acquisition System



Real-time detection of P,Q,R,S,T peaks

(using DTW Dynamic Time Warping)

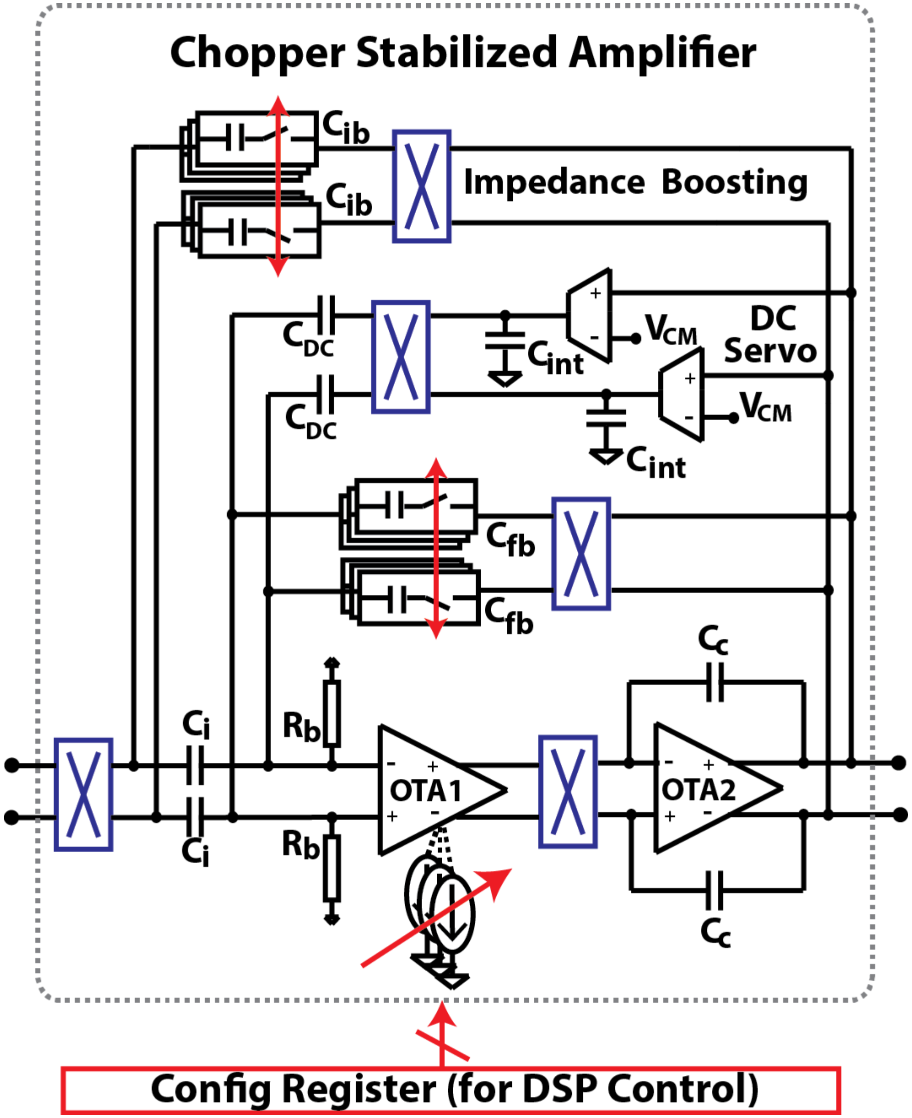


Prediction using LMS-based adaptive filter

Amplifier power reduction

Dynamic reconfiguration of noise modes

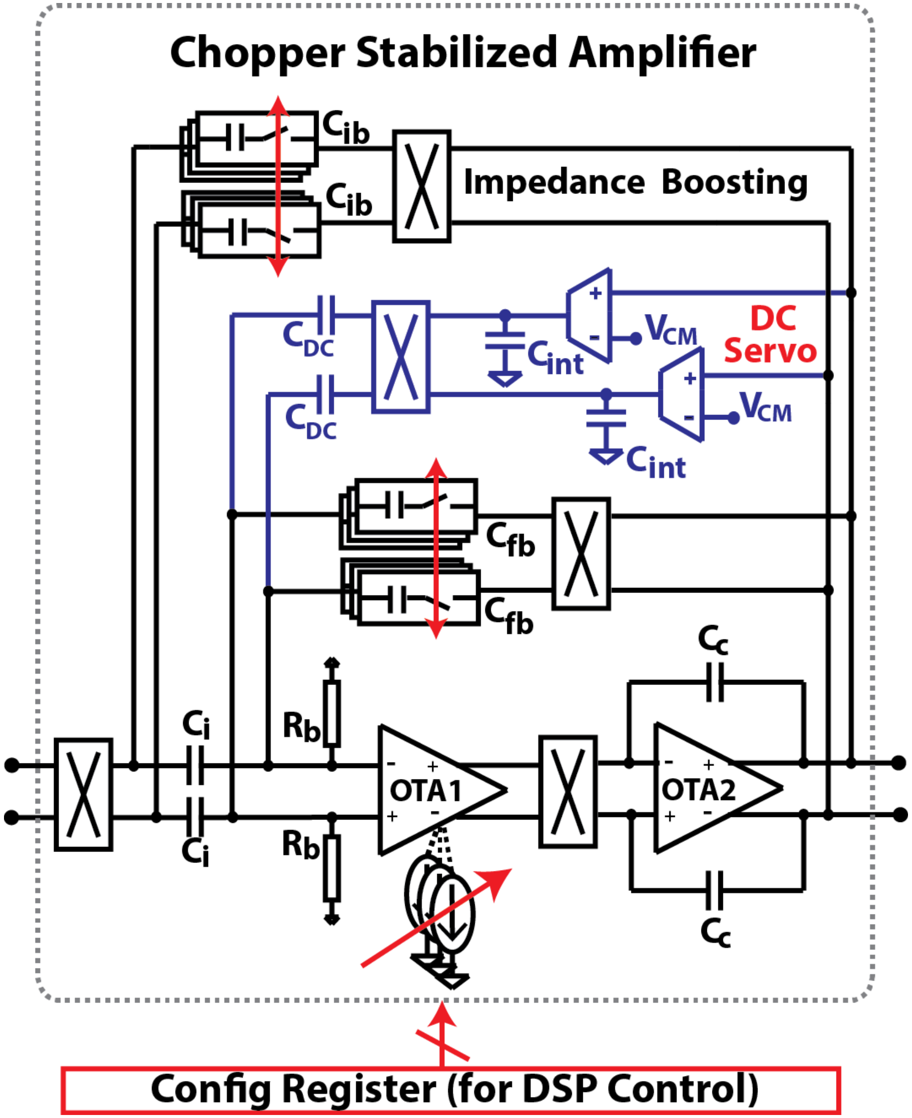
Reconfigurable AFE: Amplifier



AFE Challenges:

- In-band flicker noise
- High CMRR (for 60Hz interference)
- High electrode polarization offset
- High input impedance requirement

Reconfigurable AFE: Amplifier



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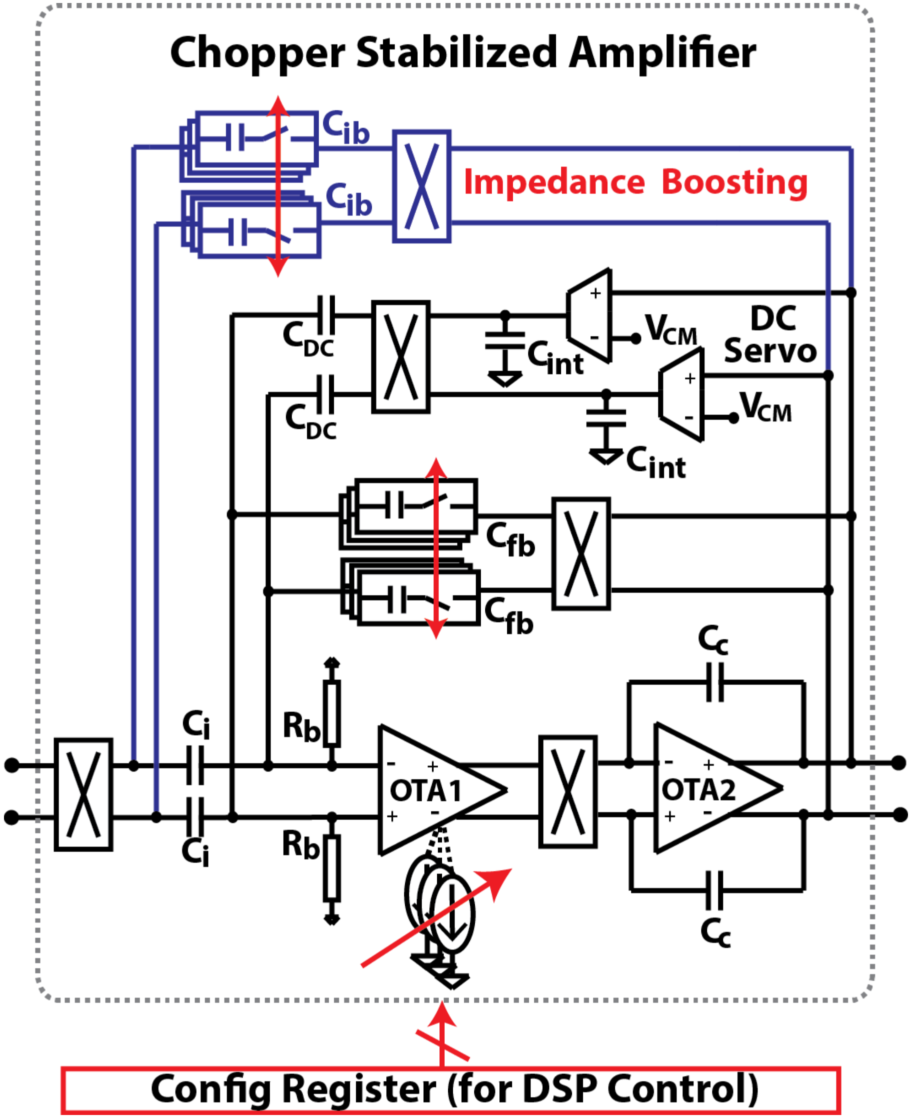

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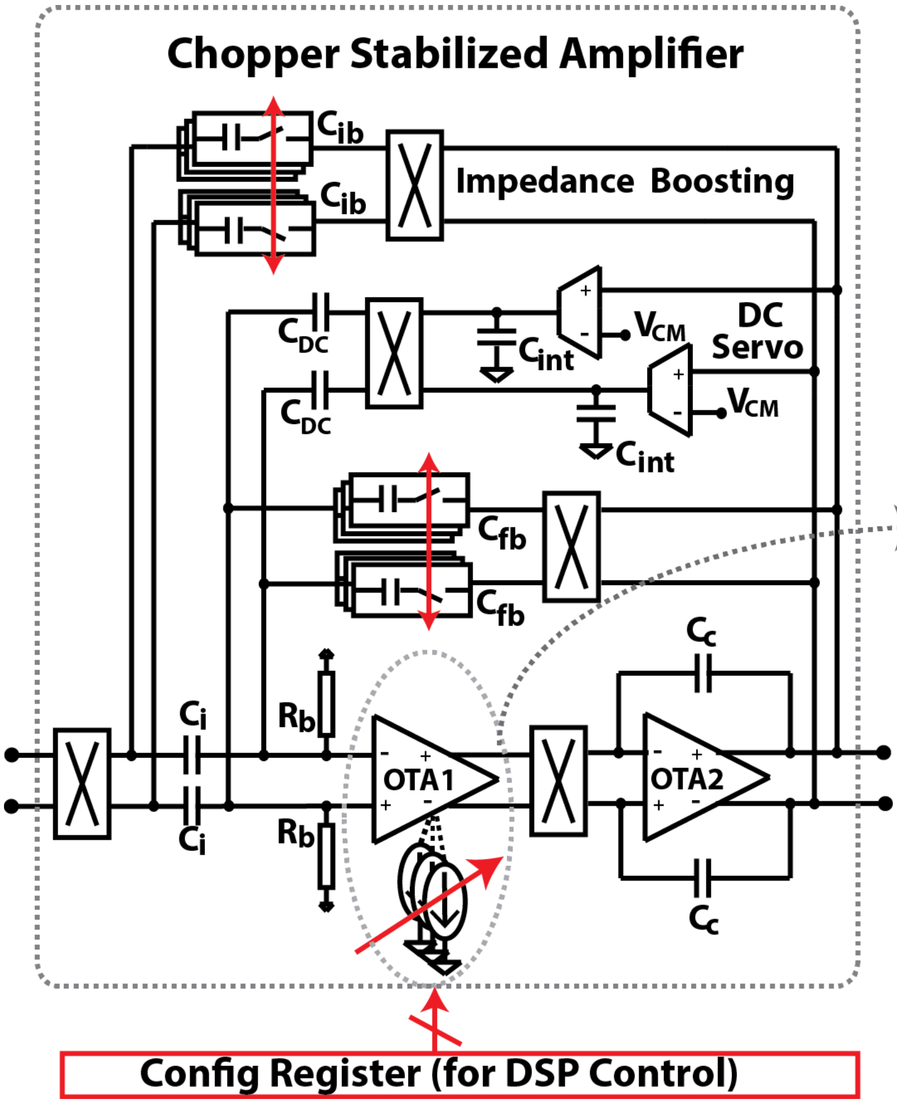
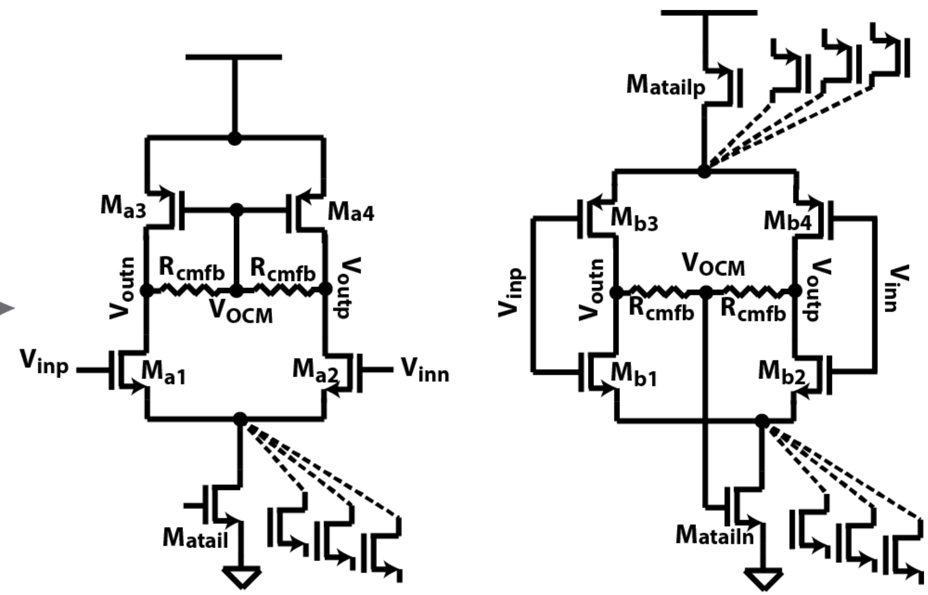


Noise Reconfiguration:

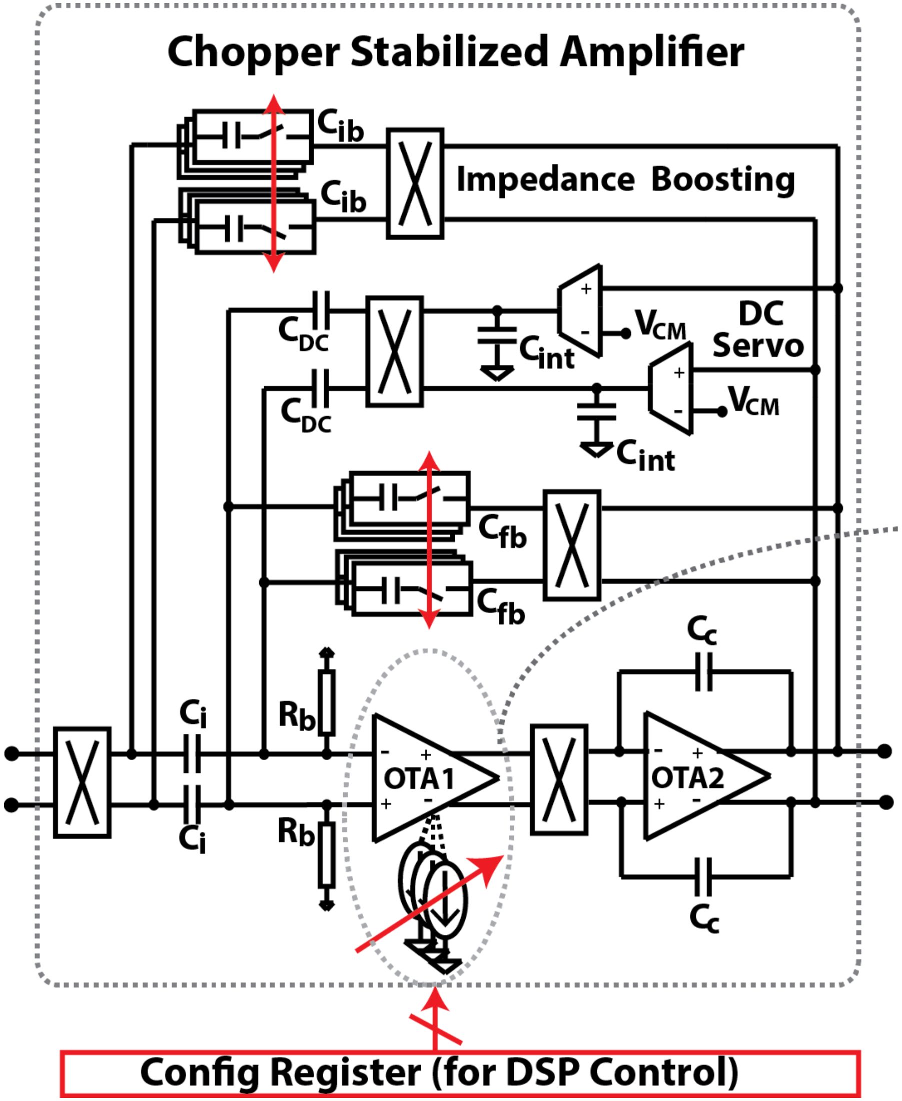
OTA Topology Selection



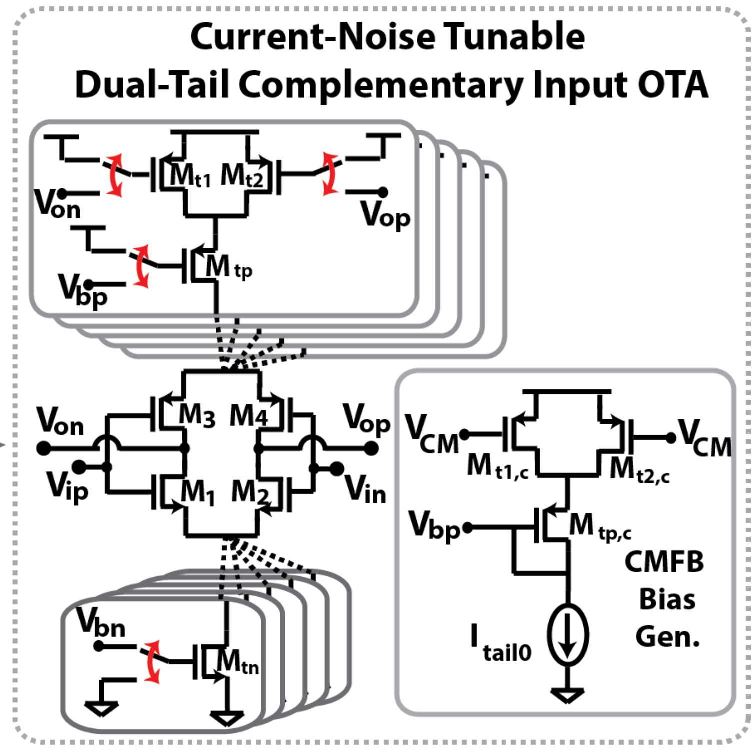
Single-tail vs. Dual-tail OTA

- ❖ Constant CM for wide current
- ❖ CMFB issue – open loop gain changes with current

Reconfigurable AFE: Amplifier



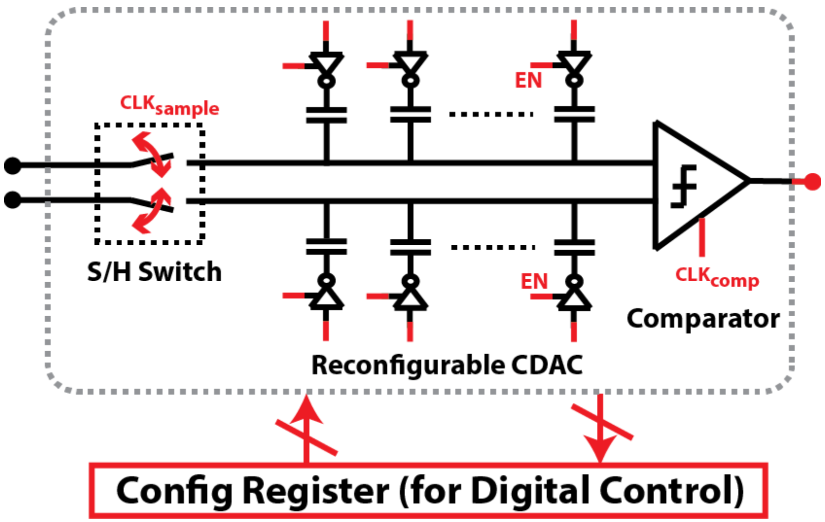
Noise Reconfiguration:



- Wide current tuning range (100 nA – 675 nA)
- Better noise efficiency

Reconfigurable AFE: ADC

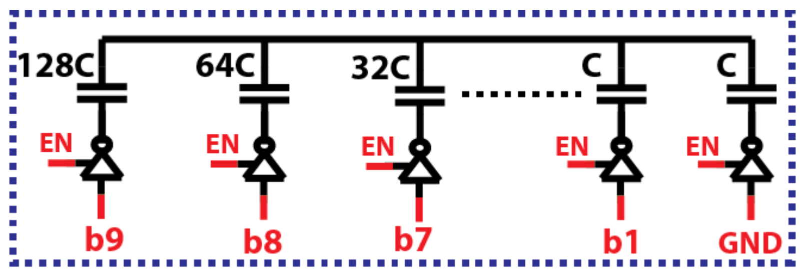
SAR ADC



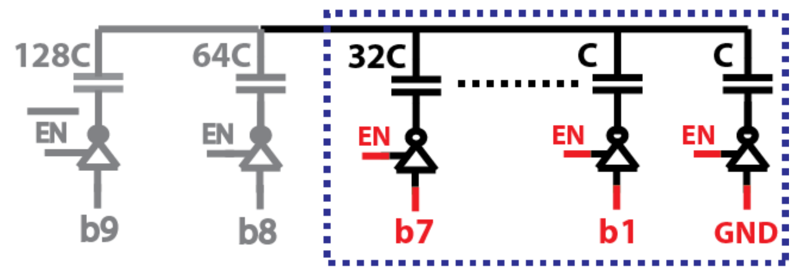
Reconfiguration:

- Sampling rate
- Resolution

9-bit Mode:

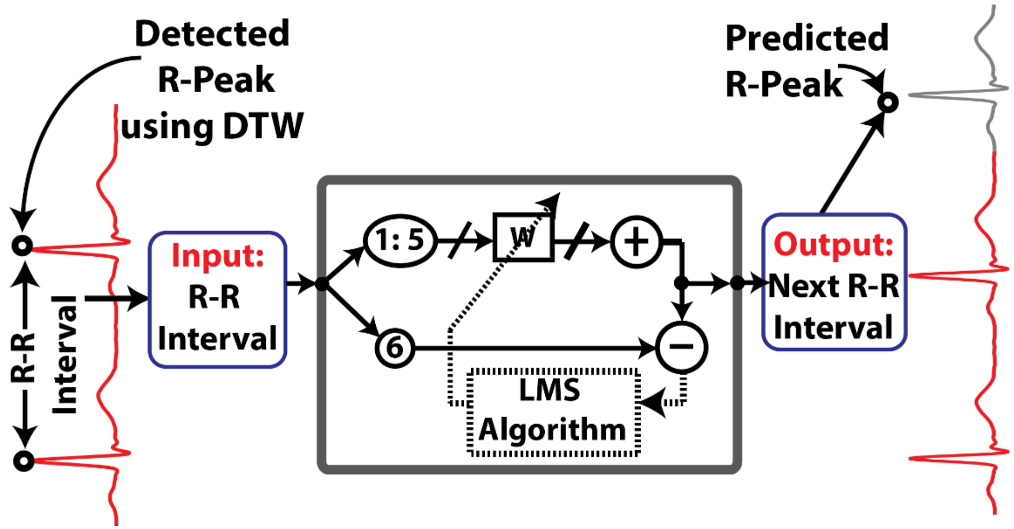


7-bit Mode:



Digital Back-End Functionality

LMS-based Adaptive Linear Predictive Filter



$$y[n] = w_1[n] * x[n-1] + \cdots + w_N[n] * x[n-N]$$

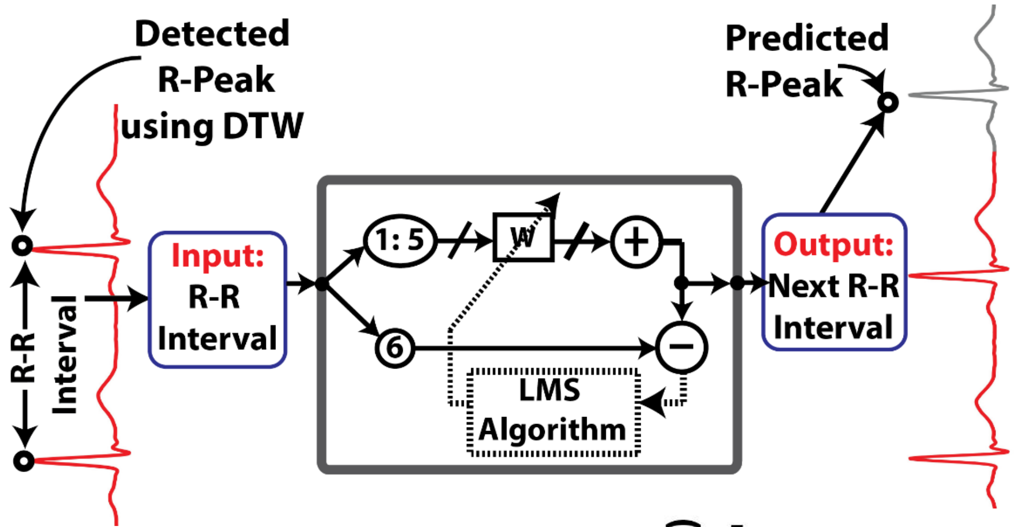
$$e[n] = y[n] - x[n]$$

$$w_i[n+1] = w_i[n] + \mu * x[n-i] * e[n]$$

$x[n]$: Detected R-R interval, $y[n]$: Predicted R-R interval,
w_i: Adaptive-filter coefficients, μ: Adaptation parameter.

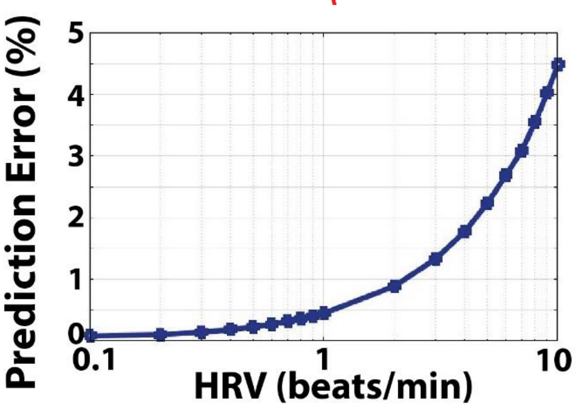
Digital Back-End Functionality

LMS-based Adaptive Linear Predictive Filter



❖ Prediction independent of the feature-extraction algorithm (e.g., DTW)

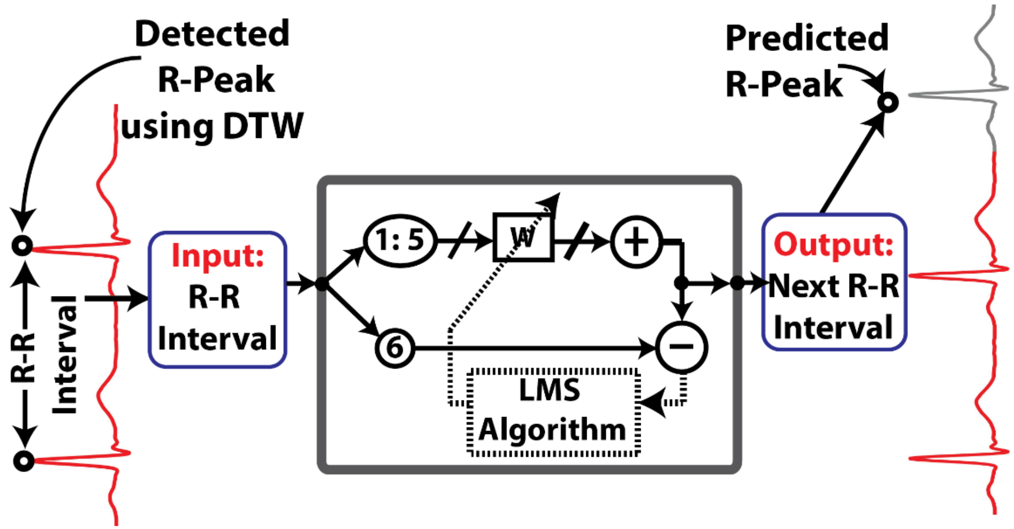
❖ 5^{th} order filter sufficiently accurate for quasi-periodic ECG with typical heart-rate variability (HRV)



$$\text{Prediction Error} = \frac{\text{Std. Dev. [predicted – detected R--R Intervals]}}{\text{Avg. detected R--R Intervals}}$$

Digital Back-End Functionality

LMS-based Adaptive Linear Predictive Filter

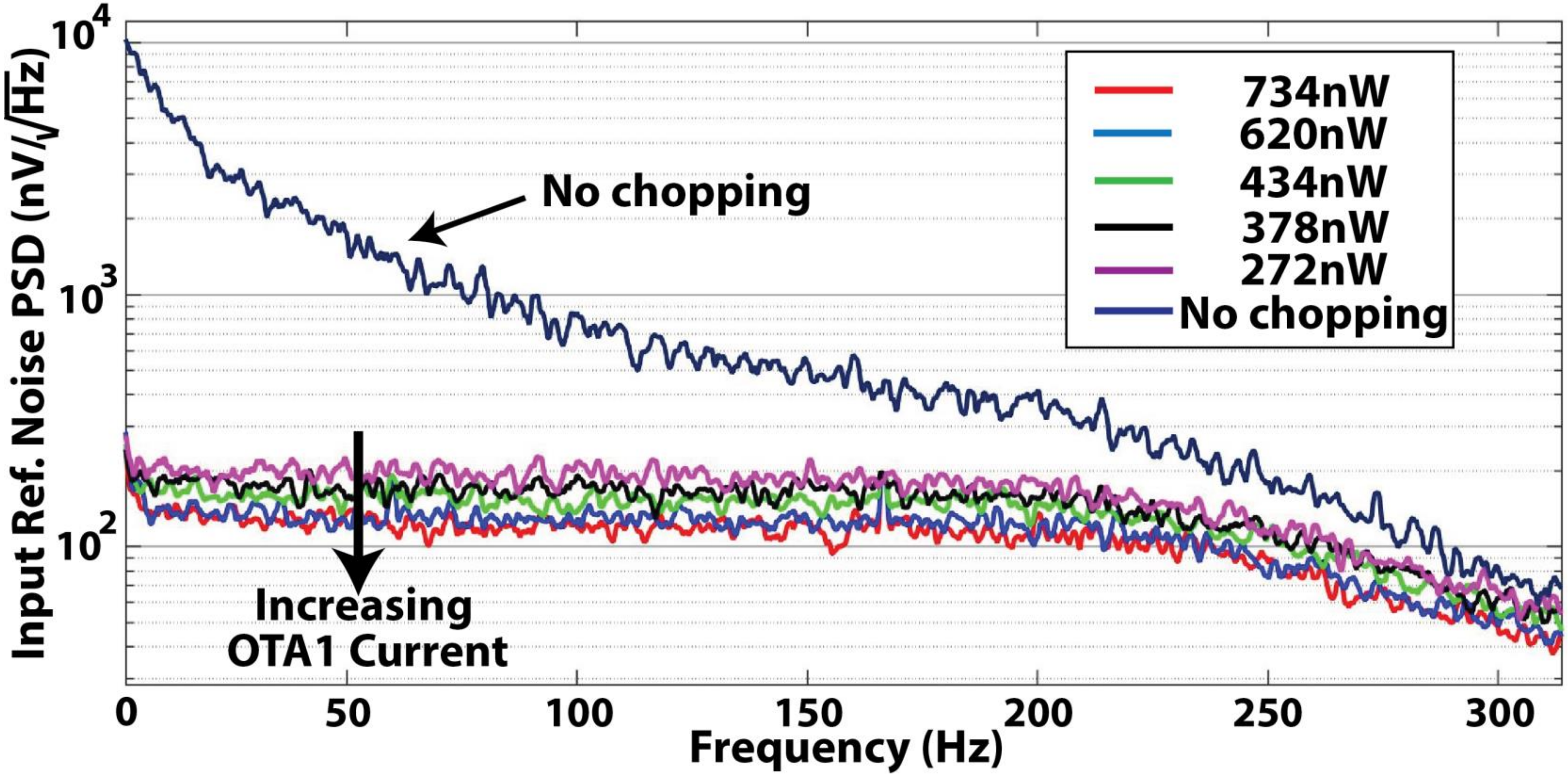


- ❖ One prediction per heart beat (72 beats/min)
- ❖ Operation at ~1 Hz
- ❖ Simulated < 10nW power

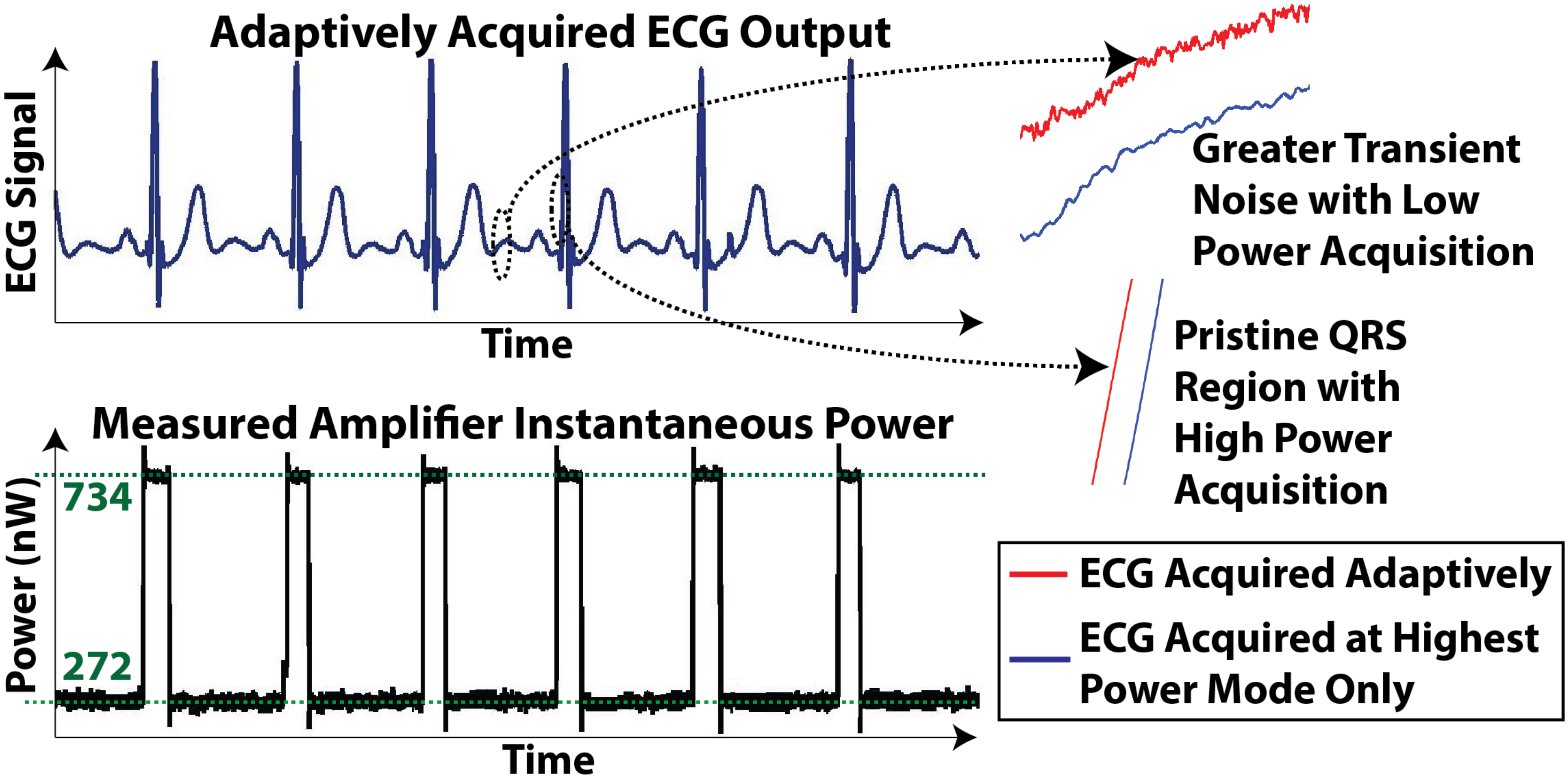
Negligible power overhead for reconfiguration!

Noise Power Trade-off

Measured amplifier input-referred noise



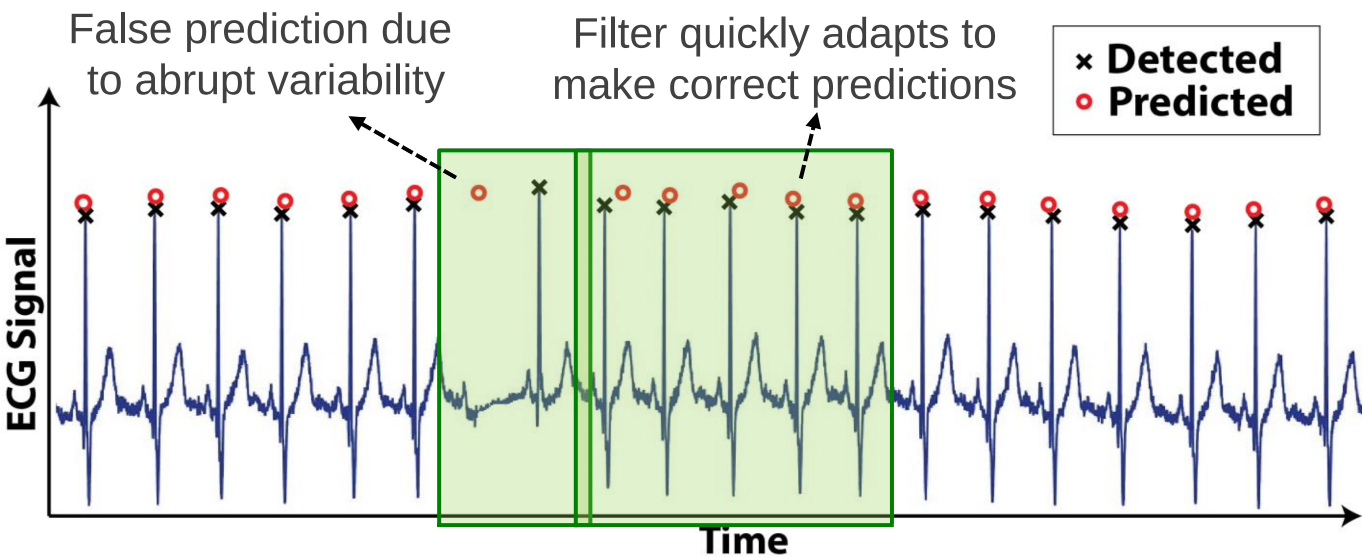
Data-Dependent Power Savings



2.5× data-dependent power reduction!

Adaptive Acquisition Performance

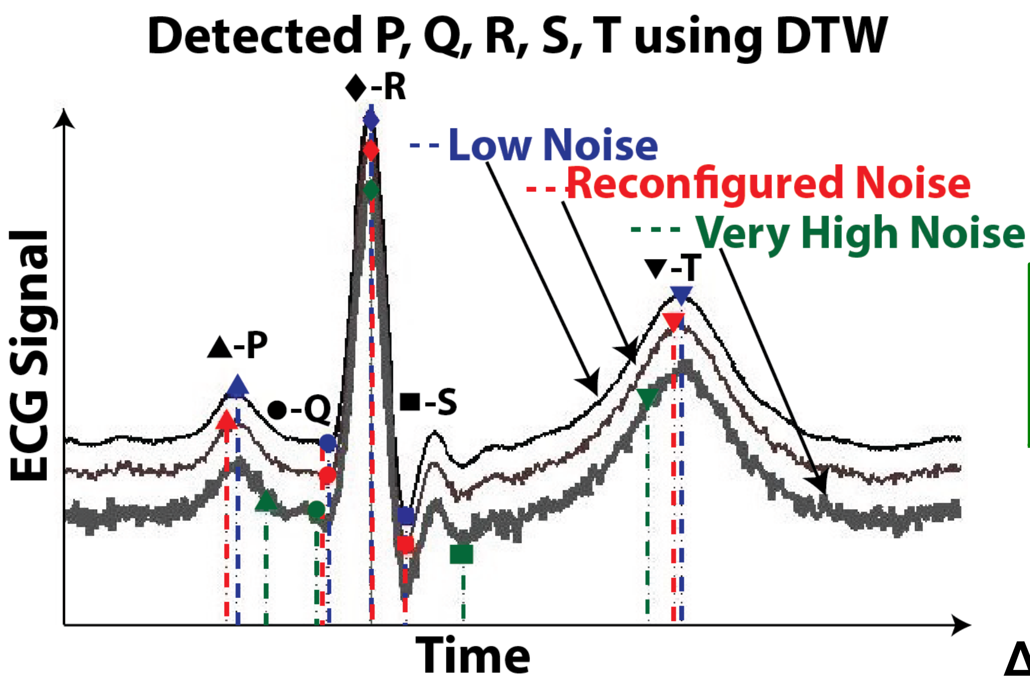
Performance characterized using ECG data from MIT-BIH Arrhythmia database



- ❖ Power savings over prolonged duration of slow HRV
- ❖ Recurring false prediction with extreme irregular cardiac activity is itself an indicator of an anomaly

No compromise in anomaly detection capability!

Adaptive Acquisition Performance



Peak Detection Errors

	$\sigma_{\Delta t}$ (ms)	$\sigma_{\Delta t}/T_{avg}$ (%)
Q	2.27	0.29
R	2.19	0.28
S	2.42	0.31
P	12.01	1.53
T	16.72	2.13

Δt – Peak positions in data acquired adaptively relative to that when AFE is always in high power mode

T_{avg} – Avg. separation between consecutive peaks

< 0.35% in extracted signal metrics of interest!

Performance Comparison

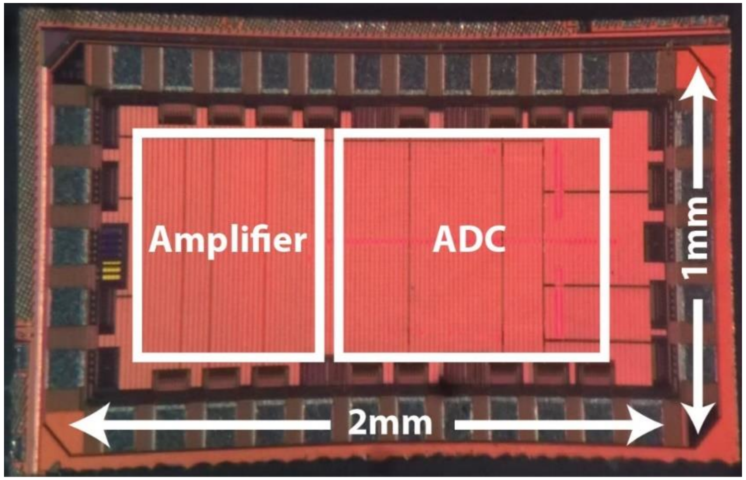
	This work	ISSCC'15	ISSCC'14	ISSCC'14	VLSI'12	JSSC'11
Application	ECG	ECG	ECG	ECG	ECG	ECG
Supply (V)	0.8	0.6	1.3	0.6	0.6	1.8
Amplifier						
Power (nW)	272 – 734#	1	559*	16.8	831*	10,600*
Gain (dB)	22 – 43	32	31-43	51 – 96	35 – 70	40 – 60
BW (Hz)	250	370	130	250	156	170
Integ. Noise (μV_{rms})	1.90 – 2.91#	26	4.9	6.52	3.44	1.1
CMRR (dB)	82	60	90	–	70	105
ADC						
Power (nW) @1 kSps	34.6**	1.1	67*	1.8 (500 Sps)	19‡	4,400 (2 kSps)
Resolution	5-9	10	7-9	8	9	11
F_{sample} (kSps)	1-10	1.1-100	0.512	0.5	–	2
$ENOB_{max}$	8.75	9.2	8.96	7.14	8.01‡	10.6
INL (LSBs)	0.58	0.87	–	1.8	0.55	0.3
DNL (LSBs)	0.80	0.96	–	1	0.48	0.5
AFE System						
Power (nW)	307 – 769†	3	626	18.6	850	14,000
Tunable Knobs	Noise, Av, #Bits	–	Av, #Bits	Av	Av	Av, BW
P_{Amp}/P_{ADC}	7.86 – 21.2	0.91	8.34	9.33	43.74	2.41

† The DSP control and SAR logic were implemented off-chip on an FPGA and are not reported. **ADC in 9-bit mode.
# AFE in 35 dB gain mode. ‡Estimated from reported SNDR and FOM. *From reported component-wise breakdown.

Demonstrated activity-dependent amplifier power savings!

Conclusion

- Dynamic noise-power trade-off in amplifier
- Aided by LMS filter with negligible power overhead
- Data-dependent signal acquisition demonstrated to achieve 2.5× power reduction
- Useful technique particularly for IoT mHealth applications



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