ASP-DAC 2011
DESIGNERS' FORUM

YOKOHAMA

Holst Centre

Open Innovation by IMEC and TNO

imec

HUMAN++: WIRELESS AUTONOMOUS SENSOR TECHNOLOGY FOR BODY AREA NETWORKS

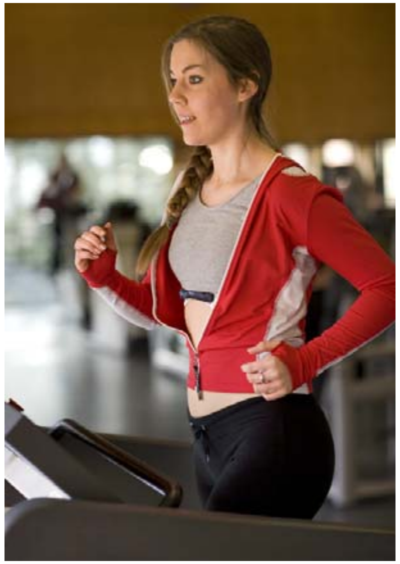
VALER POP

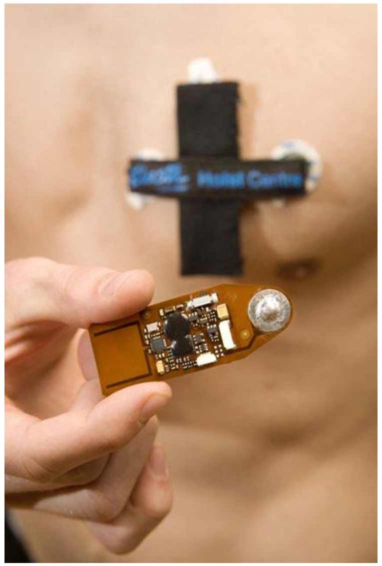
IMEC/HOLST CENTRE

WITH SUPPORT FROM RUBEN DE FRANCISCO, HANS PFLUG, JUAN SANTANA, HUIB VISSER, RUUD VULLERS, HARMKE DE GROOT, BERT GYSELINCKX

HUMAN++ VISION

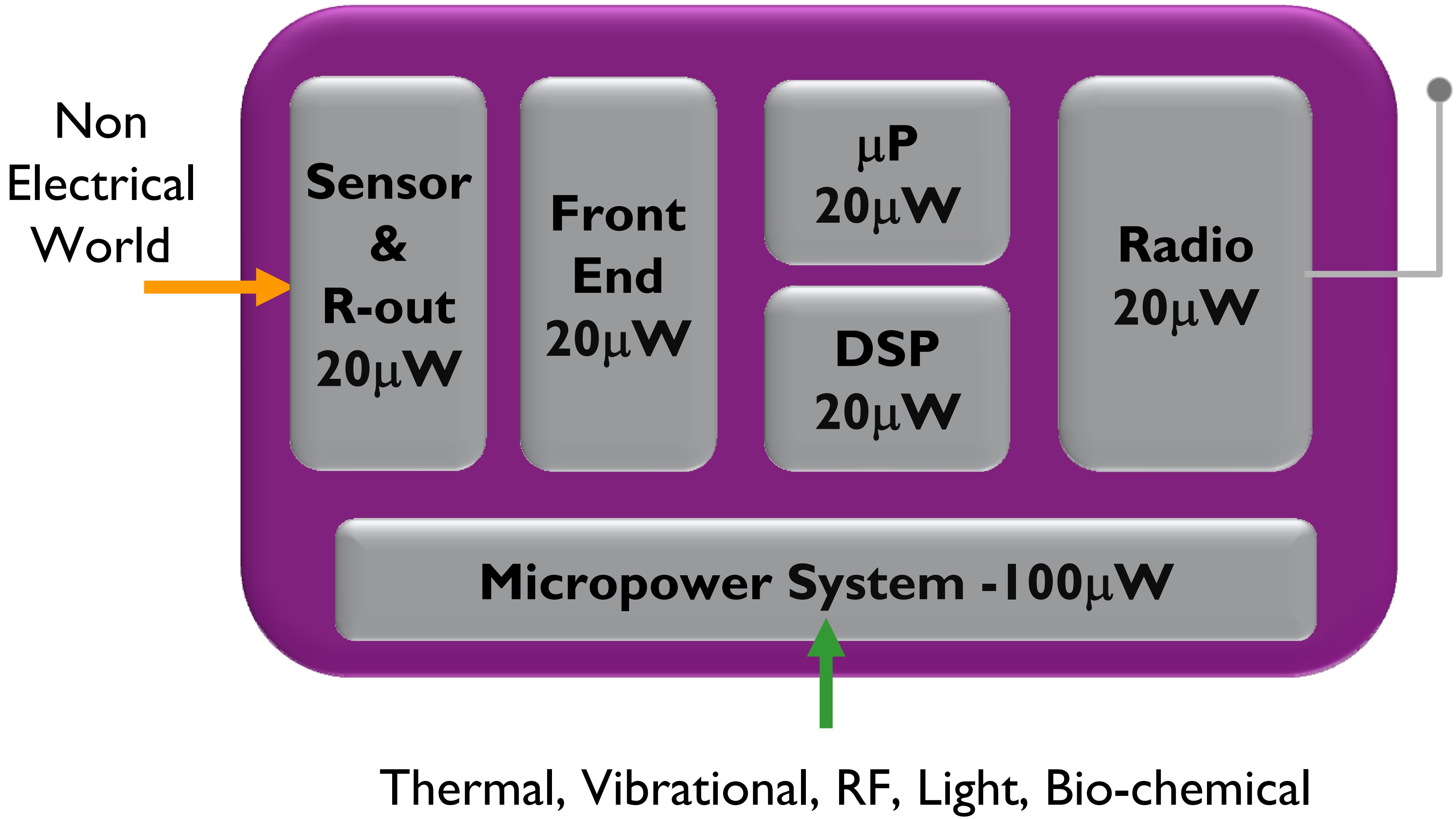
BODY AREA NETWORKS(BAN) AT IMEC
Enabling wearable and personal health





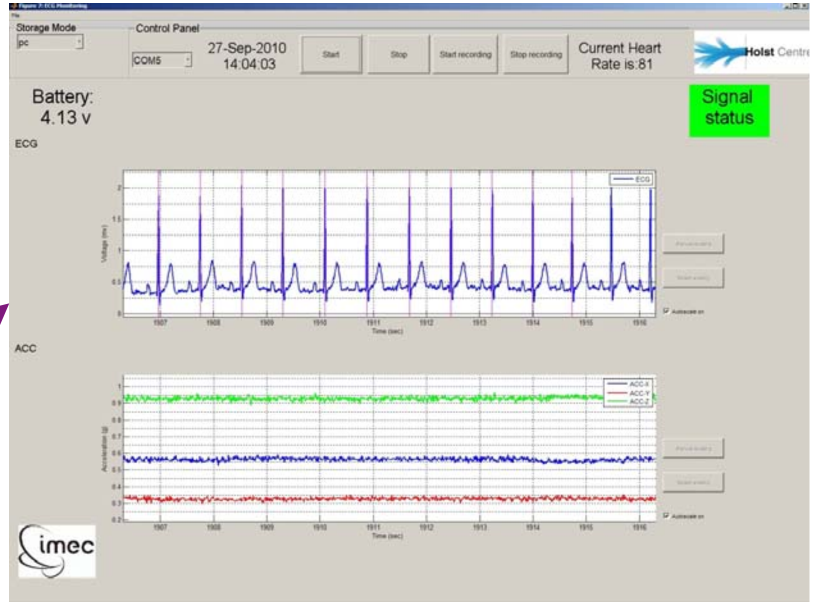
SUPPORTED BY A PROFESSIONAL ORGANIZATION AND INFRASTRUCTURE

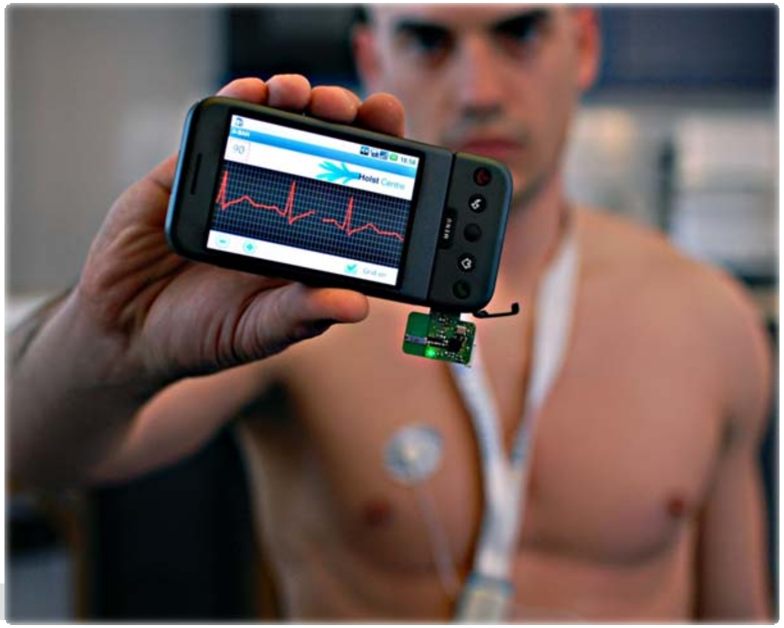
ULTRA LOW POWER TECHNOLOGY FOR WIRELESS AUTONOMOUS TRANSDUCERS



Architectural-level approach important!

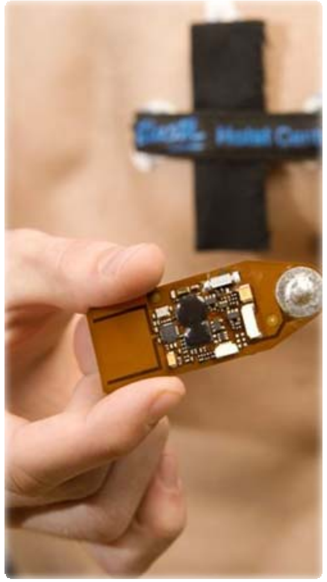
THE IMEC ROUTE TO A THIN FLEXIBLE PATCH STARTS WITH A NECKLACE

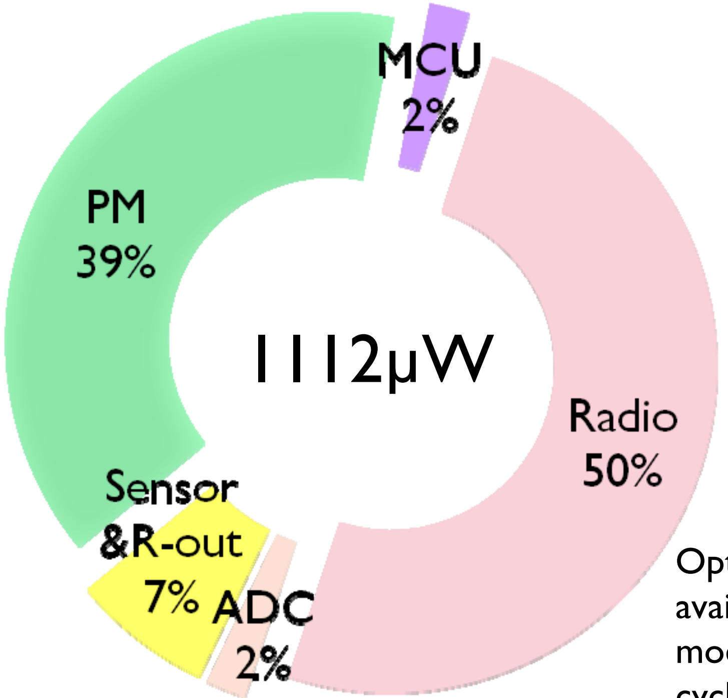




Necklace with arrhythmia analysis and continuous wireless ECG signal transmission

GOING TO A PATCH IS NOT JUST CHANGING THE FORM FACTOR : POWER IS THE MAIN ISSUE





Optimally using all available power modes and duty cycling

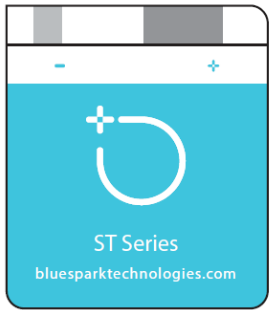
Component	V_{dd}
μC: MSP430	2.2
Radio: Nordic nRF24L01	2.2
ADC: MSP430	2.2
Power Manager: TP780	
Bio-potential: imec	3.0
Battery: 140 mAh Li-Ion	3.7
Arrhythmia	remote

Autonomy on 140 mAh secondary battery: 19 days

Assume 6 cm^2 printed thin film primary battery (e.g Blue Spark ST: 1 mAh/cm^2 @ 1.5V):

Autonomy on printed battery: 8 hours

Should be improved by 22x, i.e. 50μW



BAN SYSTEM ARCHITECTURE; POWER DIAGNOSIS BY MODELING

Application

Power diagnosis

Power optimization

$\max[(P_G - P_C - P_L)/V]$

Wearable	Low-power	Autonomous
Comfortable: flexible, thin Medical grade quality Monitor arrhythmia patient Works well in daily life, e.g. sports		At least 7 days autonomy when battery powered Autonomous by energy harvester Under 100µW power consumption

Test & optimization

System design

Design optimization

P_G Power generated
P_C Power consumption
P_L Power loss
V System volume

POWER DIAGNOSIS BY MODELING; ANALOG-TO-DIGITAL CONVERTER & RADIO

1. Analog-to-Digital converter power modeling

$$P_{ADC} = V_{dd}^{2} L_g f_s 10^{k_1 ENOB - k_2}$$

2. Radio modeling

- free-space path loss model → link budget computation

$$L_{path}(d, f_c) = 20 \log_{10}(d) + 20 \log_{10}(f_c) - 147.5$$

- select the minimum transmit power available

$$P_{tx} \geq L_{path}(d_{\min}, f_c) + P_{sens}$$

Analog-to-Digital Converter
V_{dd} the supply voltage
L_g the CMOS technology gate length
f_s ADC sampling frequency
k_1, k_2 parameters related with the ADC speed
ENOB the effective number of bits

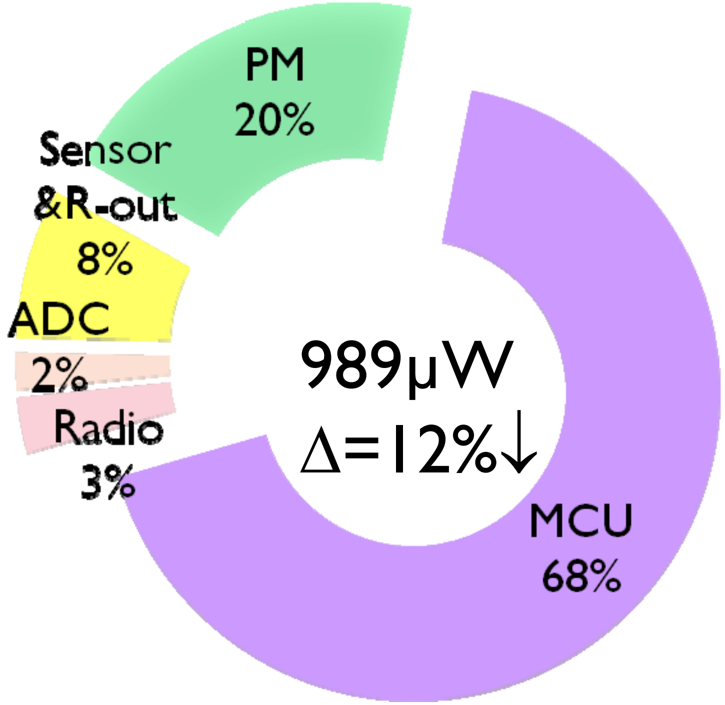
Radio
L_{path} path length
d the distance transmitter-receiver
f_c the carrier frequency
P_{sens} sensitivity level

imec

POWER DIAGNOSIS BY MODELING; POWER OPTIMIZATION STRATEGY

Reduce radio power; choices

•More power efficient radio
•Local processing of arrhythmia algorithms
This reduces number of samples to be transmitted



Component	V_{dd}
μC: MSP430	2.2
Radio: Nordic nRF24L01	2.2
ADC: MSP430	2.2
Power Manager: TP780	
Bio-potential: imec	3.0
Battery: 140 mAh Li-Ion	3.7
Arrhythmia	local

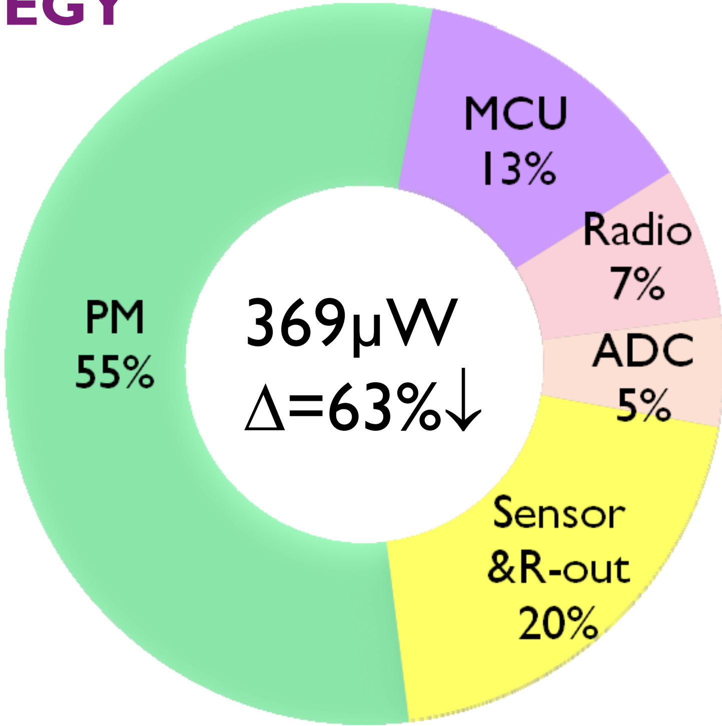
Processor power dominated

POWER DIAGNOSIS BY MODELING; POWER OPTIMIZATION STRATEGY

Reduce processor power

Use Cortex M3 based processor with embedded frequency and power management (130nm instead of 180nm)
Optimize implementation of algorithm for the processor: biggest gain...

Component	V_{dd}
µC: **EFM32G890**	2.2
Radio: Nordic nRF24L01	2.2
ADC: MSP430	2.2
Power Manager: TP780	
Bio-potential: imec	3.0
Battery: 140 mAh Li-Ion	3.7
Arrhythmia	local



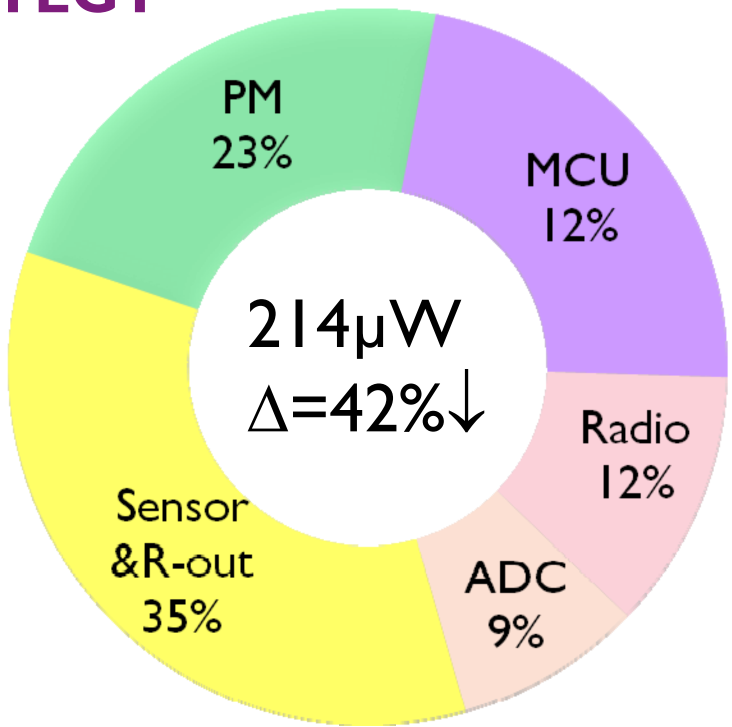
Power management power dominated

POWER DIAGNOSIS BY MODELING; POWER OPTIMIZATION STRATEGY

Reduce power management power

Originally, a linear regulator used: dissipates power caused by difference Battery voltage – Operating voltage

Replaced by switching regulator of Linear Technologies



Component	**V_{dd}**
µC: EFM32G890	2.2
Radio: Nordic nRF24L01	2.2
ADC: MSP430	2.2
Power Manager: **LTC3100 +C**	
Bio-potential: imec	3.0
Battery: 140 mAh Li-Ion	3.7
Arrhythmia	local

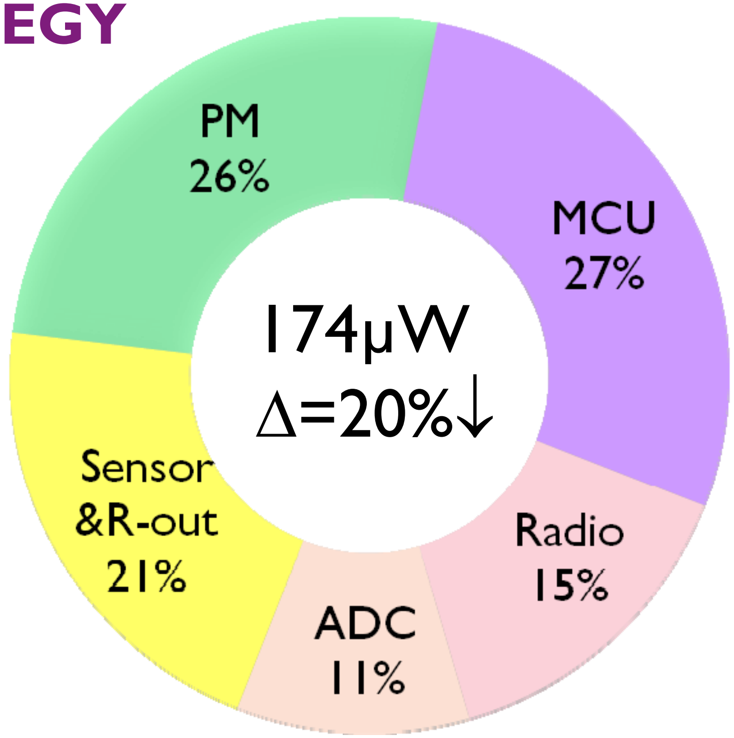
Biopotential power dominated

POWER DIAGNOSIS BY MODELING; DESIGN OPTIMIZATION STRATEGY

Reduce bio-potential power

Reduce power supply voltage of bio-potential chip to same voltage as digital
Reduces also power management losses

Challenge to obtain same noise level!



Component	V_{dd}
µC: EFM32G890	2.2
Radio: Nordic nRF24L01	2.2
ADC: MSP430	2.2
Power Manager: LTC3100+C	
Bio-potential: imec	2.2
Battery: 140 mAh Li-Ion	3.7
Arrhythmia	local

Autonomy off necklace: 2.5 months

Autonomy on printed battery of 6cm^2: 1.5 days

FYI: replacing the Nordic radio by Bluetooth Low Energy would increase the power to 232µW (Δ=33%↑)

Power consumption pretty balanced

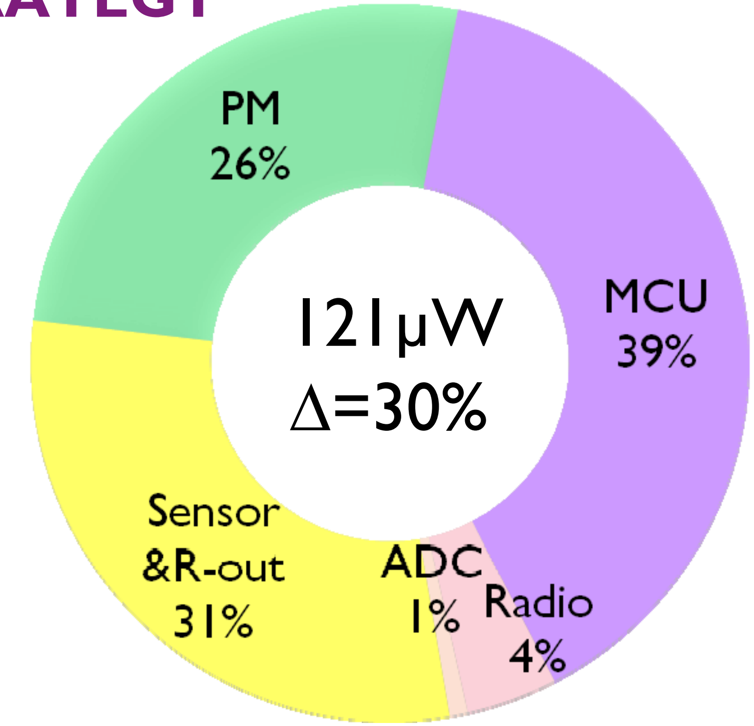
POWER DIAGNOSIS BY MODELING; DESIGN OPTIMIZATION STRATEGY

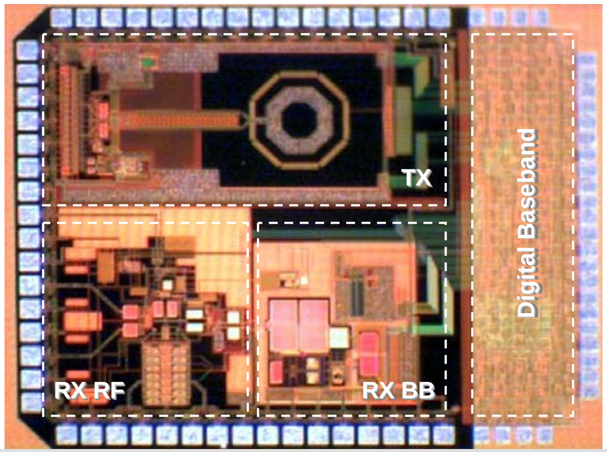
Low-power design

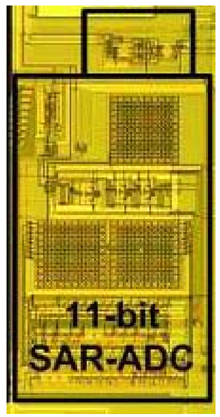
Replace the Nordic radio by own design

Replace the MSP ADC by own design

Component	V_{dd}
µC: EFM32G890	2.2
Radio: **imec**	**1.2**
ADC: **imec**	**2.0**
Power Manager: LTC3100+C	
Bio-potential: imec	2.2
Battery: 140 mAh Li-Ion	3.7
Arrhythmia	local







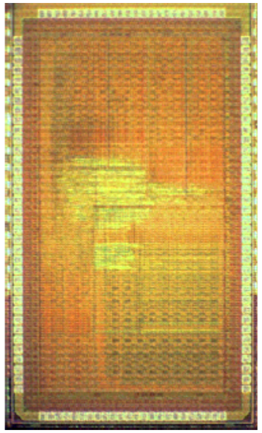
POWER DIAGNOSIS BY MODELING; DESIGN OPTIMIZATION STRATEGY

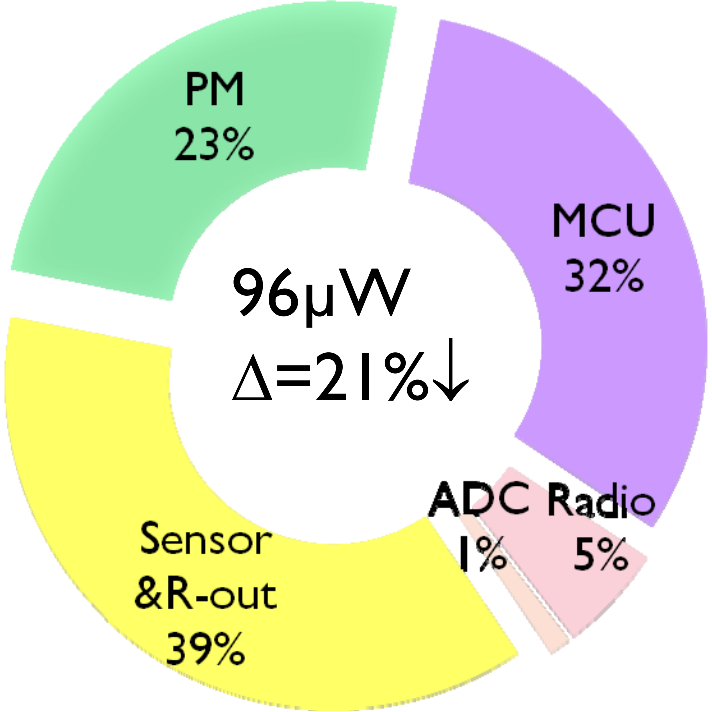
Low-power design

Replace the processor by own design

A-SSCC 2010
IEEE Asian Solid-State Circuits Conference

Replace battery by Panasonic battery





Component	V_{dd}
μC: **imec**	**1.2**
Radio: imec	1.2
ADC: imec	2.2
Power Manager: LTC3100+C	
Bio-potential: imec	2.2
Battery: **140 mAh Li-Ion**	**2.4**
Arrhythmia	local

Autonomy off necklace: 3.5 months

Autonomy on printed battery of $6cm^2$: 2.2 days

Power diagnosis by modeling based on measured component power of real Si

WHAT IS STILL POSSIBLE TO REACH 50μW?

1. Reduce processor V_{dd} to 0.7V
   - Works! Paper in press. at ISSCC2011
2. Reduce supply voltage instrumentation amplifiers to 1.2V
   - Works! Paper in prep. for VLSI 2011
3. Reduce battery voltage to 1.5V
   - Possible since all circuits operate on 1.2V

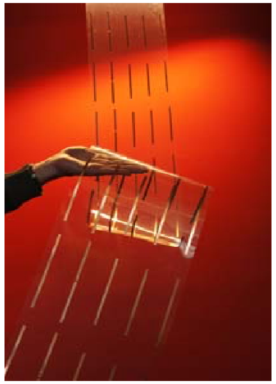
Bottom line

- Estimated power consumption: 51 μW
- Autonomy on 6 cm^2 thin film printed battery: 6 days

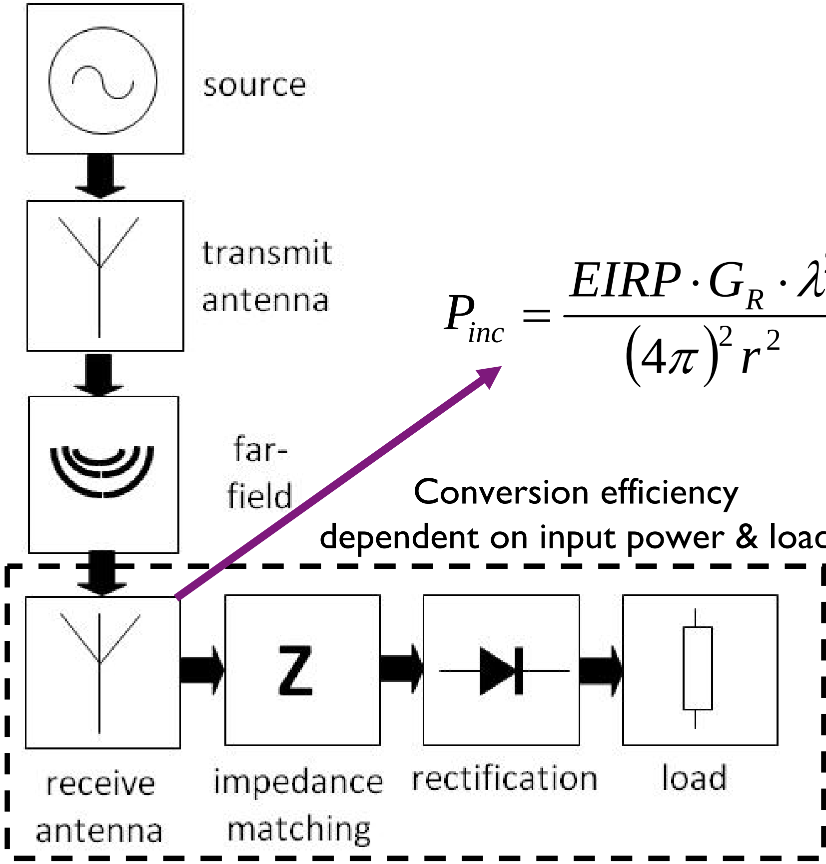
Could we replace the primary battery with energy harvesting?

- Radio-Frequency (RF)
- Thermo-electric generator
  - Works! Paper in prep. for VLSI 2011

COULD WE REPLACE THE PRIMARY BATTERY WITH RADIO-FREQUENCY HARVESTER?

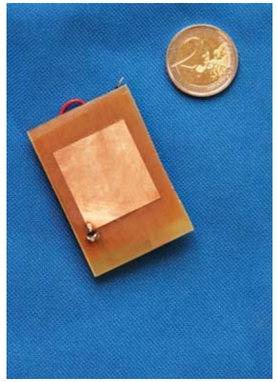


Flexible RF harvester (imec)



$$P_{inc} = \frac{EIRP \cdot G_R \cdot \lambda^2}{(4\pi)^2 r^2}$$

Conversion efficiency dependent on input power & load



Rigid RF harvester (imec)

RF harvester power

Area 40x55mm

100µW at P_{inc}=-4dBm

& 2.45GHz

P_{inc} power incident upon the rectifying circuit
G_R the receive antenna gain
r distance transmit - receive antenna

EIRP Effective Isotropic Radiated Power
λ the used wavelength

CONCLUSION

It is time to make electronics autonomous

- Needs autonomous interfacing to the world
- Needs architectural power diagnosis and power optimization
- Electronics will evolve from toys-for-boys to hidden electronics that helps solving the grand challenges our society faces
- Bringing sensors to the right power point requires full system view, multi-disciplinary effort

ASPIRE
INVENT
ACHIEVE

Holst Centre

Open Innovation by IMEC and TNO

imec