Wireless Body Sensor Networks for Healthcare Applications: Challenges in Energy Consumption

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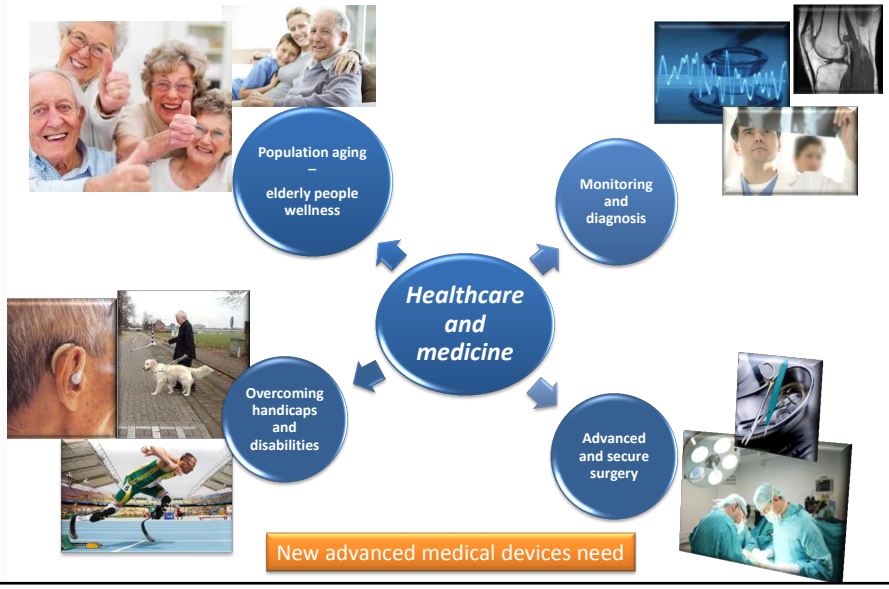
Healthcare: new societal challenges

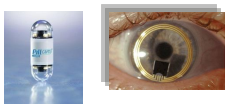


2

Which devices for which medicine?

- External and/or disposable devices
  - Intervention catheters, endoscopes, drug delivery systems, health monitoring

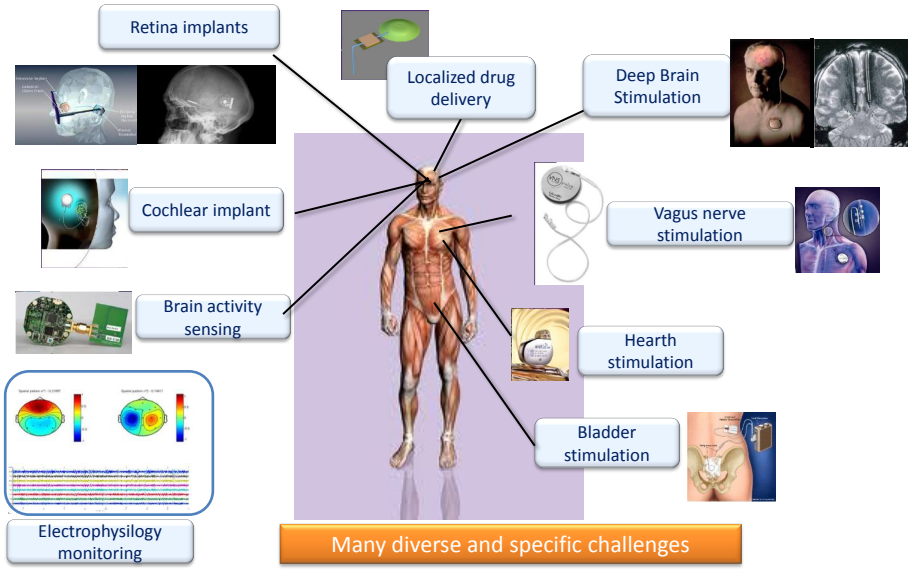
- Temporarily implanted devices
  - Smart pills, intraocular pressure sensors



- Long-term implantable devices
  - CRT (Pacemaker), Vagusnerve stimulation

3

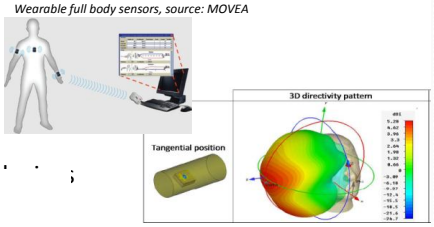
Implantable Devices for New Medecine



Wireless Monitoring and Networking

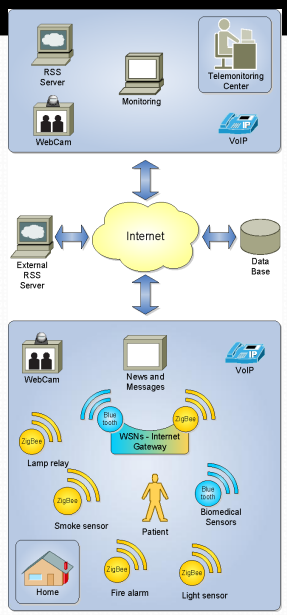
- Wireless monitoring
  - Wearable monitoring devices
  - Implantable or embedded antenna in devices

Wearable full body sensors, source: MOVEA



Antenna radiation in hearing aid device,
L. HUITEMA et al. CEA LETI 2012

- New Infrastructure for medical networking



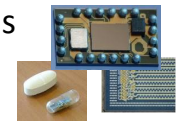
5

Applications Challenge the Technology

Requests from clinicians:

- Efficacy
- Localized and live monitoring
- Fast data analysis
- Reliability
- Price

… with translate in complex technological needs



- Small form factor
- NO leads
- Easily placed and targeted
- Autonomous and communicating
- Fabricated in facilities with high degree of reproducibility and reliability

[after Yann LAMY, CEA LETI]

6

“Just be still Jim….”

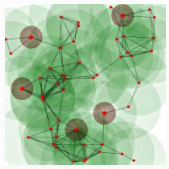
7

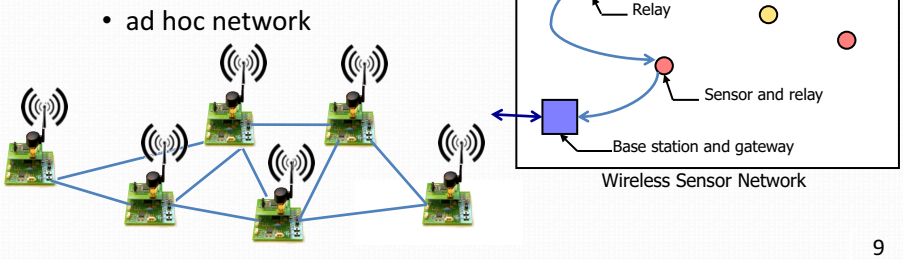
Agenda

- Introduction, challenges and objectives
- Wireless (Body) Sensor Networks
  - Applications, system requirements
- Generic architecture of a WSN node
  - Processor and radio transceiver performance
- Examples of WBSN for health-care applications
- Energy efficient protocols (Rx)
  - MAC layer
- Energy optimization of Tx power
  - Error control (LINK layer), cooperation strategies (PHY layer)
- Energy Harvesting
- Energy/power estimation and optimization
  - *Watt* is the problem?
  - Power issues in CMOS digital chips?
  - How to estimate and reduce power of hardware and software?
  - Trends in energy-efficient computer architectures

Wireless Sensor Network (WSN)

- Dense network of small nodes sensing the physical world and communicating through wireless links
  - sensing, actuating, control
  - processing, storage
  - communication, relaying
    - ad hoc network





9

WSN System Requirements

- Simplified deployment, fault tolerance
  - No maintenance and battery replacement
- Network characteristics
  - Low mean distance
  - Limited data-rate
  - Multi-hop routing
- Low cost, small size
- Long autonomy
  - Towards autonomous self-powered sensor nodes
  - 0.1-1 mW on active period

Very Low Energy Consumption

Tremendous Space of Applications

- Sensing the physical world
  - *temperature, humidity, seismic activity, building occupation, airflow, particulate detection, medical and biological parameters, etc.*
- Monitoring space: ocean water, pollution,…
- Monitoring things: robots, human body,…

Structure Health Monitoring

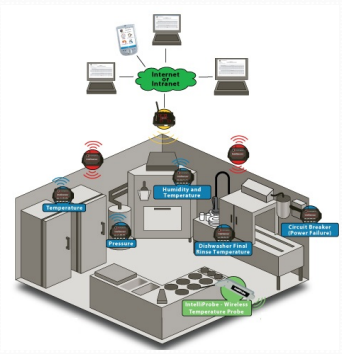
Target monitoring

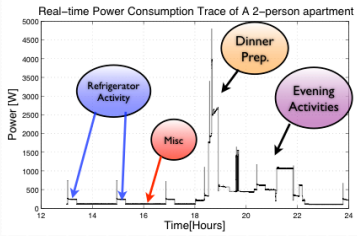
Monitoring in agriculture

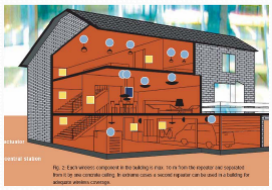
Fire detection

Emerging Applications: Indoor environment

- Smart homes and buildings
  - Home automation
  - Energy optimization
    - Intelligent lightning and heating
  - Environment monitoring (temperature, humidity, CO, gas)
  - Event monitoring: thieves, fire, flood
  - Smart metering





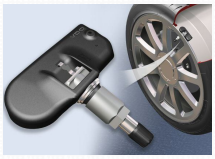


Emerging Applications: Indoor environment

- Smart factory: logistics & retail
  - Temperature monitoring for cold chain monitoring
  - Industrial control, machine health monitoring
  - Condition-based maintenance of equipment in factory
- Automatic identification
  - Asset tracking
  - Error prevention
  - Thief prevention
- Indoor localization

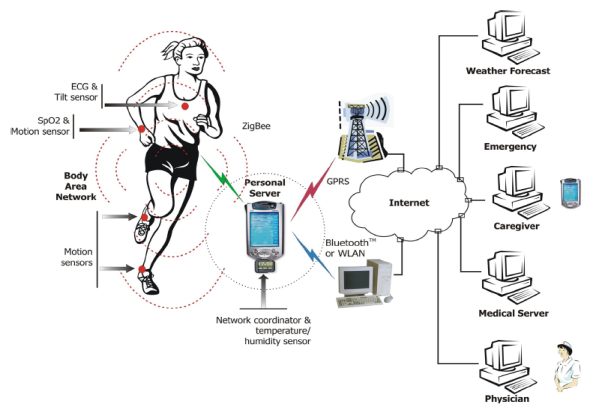
Emerging Applications: Outdoor environment

- Smart city
  - Air monitoring (temperature, humidity, noise, particles, CO, CO2, NO2, ozone)
  - Parking occupancy
- Monitor natural habitats, remote ecosystems, agriculture, forest fires
  - Water, pollution, plant monitoring
- Animals (e.g. cattle) monitoring
  - Identification, health monitoring (weight, temperature), traceability
- Disaster sites
- Structural Health Monitoring
  - Bridges, buildings
- Automotive
- Security & military surveillance



Wireless Body Sensor Networks

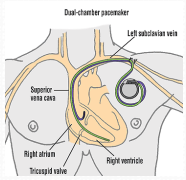
- Able to collect and send data
- Placed on the body or in the environment
- Utilize affordable ad-hoc self-managing networks

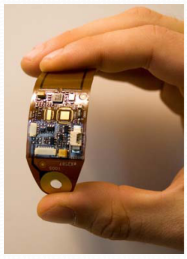


15

Applications in Medicine and Health

- Hearing aid
- Medical devices
  - Pulse oximeter, electrocardiograph (EKG), pacemaker, heart, muscle or brain stimulation
- Wireless body sensor networks
  - Heart rate, temperature
  - Electrocardiogram (ECG)
  - Electromyograph (EMG)
  - Electroencephalo-gram (EEG)
  - Blood pressure, oxygen and glucose
  - Fall detection, localization
- Smart devices with computation and communication capability
  - Watch, glasses, wristband, shoes
- E-textiles
  - Clothes with sensors, actuators and wireless link



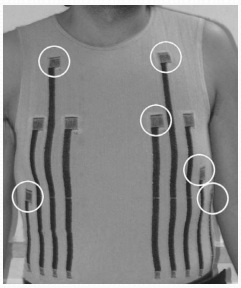


16

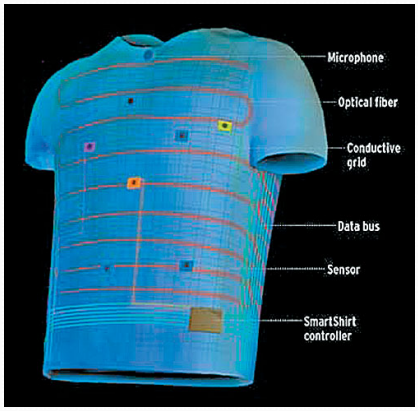
Fitness Monitoring

- Central device is smartphone or MP3 player
- Wireless headset included
- Expand functionality
  - Speed, distance
  - Heart rate, respiration monitor
  - Temperature sensor
  - Pacing information
  - Location information
  - Wristwatch display unit
  - Etc.
- Total system load < 500 kbps
- Synchronization may go faster

Wearable Monitoring Systems



Fabric electrodes have been used to monitor EKG and respiratory activity



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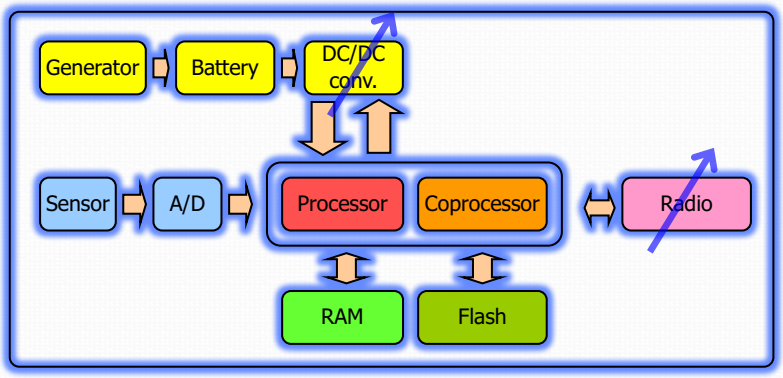
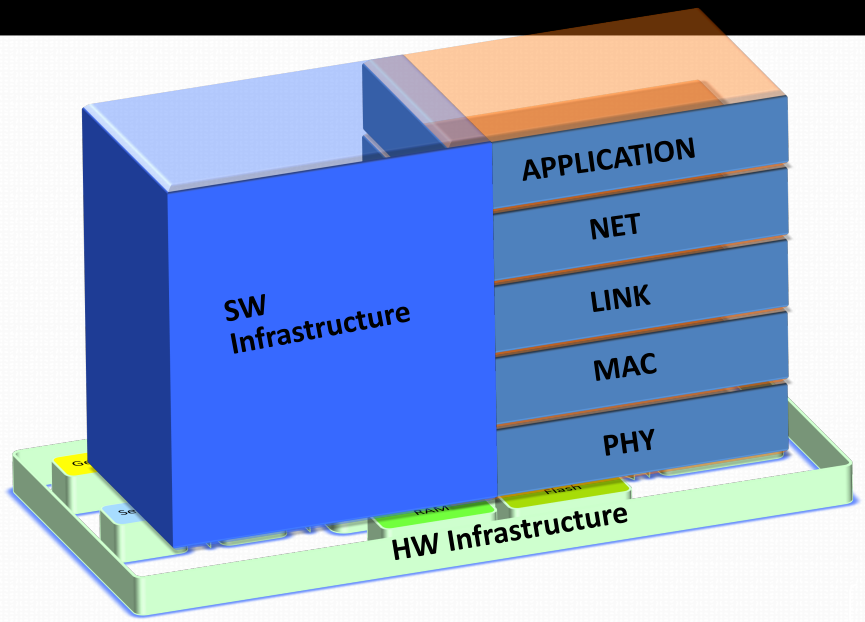
Generic Architecture of a Sensor Node

- A typical embedded system
- Main features: sense, process, store, communicate, power management



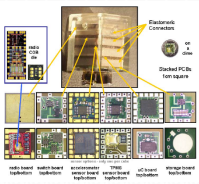
20

Generic Architecture of a Sensor Node

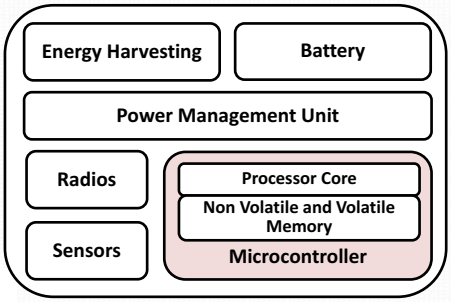


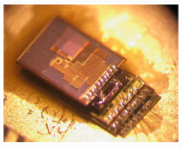
21

Wireless Sensor Node



Active power: 2.7 mW
Sleep Power: <1 µW
Flexibility +





Active power: 40 µW
Sleep Power: 11 nW
Flexibility - - -

Active power: 5-15 mW
Sleep Power: 7.8 µW
Flexibility +++

Active power: 49.5 mW
Sleep Power: 55 µW
Flexibility +++

Typical WSN Platform

- Modern low-power microcontrollers

	Device	Year	Arch.	Vdd (V)	Ram (kB)	Flash(kB)	Active[1] (mA)	Sleep (uA)	Wake (uS)
Atmel	AT128L AT256l	2002 2005	RISC 8b	2.7-5 1.8-5	4 8	128 256	0.95 0.9	5 1	6 6
Freescale	HCS08 MC13213	2003 2007	8b	2.7-5 2-3.4	4 4	60 60	7.4 6.5	1 35	10 10
Jennic	JN5139	2007	32b	2.2-3.6	192	128	3	3.3	2500
TI MSP430	F1612 F5437	2004 2008	RISC 16b	1.8-3.6	5 16	55 256	0.5 0.28	2.6 1.7	6 5
TI	CC2430	2007	8051	2-3.6	8	128	5.1	0.5	4
NXP	LPC1114 CortexM0	2010	ARM 32b	1.8-3.6	8	32	0.25	6	-

#12mW@8MHz

[Dutta, Sensys, 2008]

23

Typical WSN Platform

- Radio transceivers
  - IEEE 802.15.4 compatible

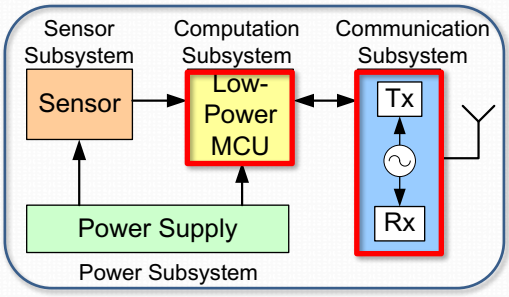
	Device	Year	Vdd (V)	RxSens (dBm)	TxPwr(dBm)	Rx(mA)	Tx (mA)	Sleep (uA)	Wake (mS)
Atmel	RF230	2006	1.8-3.6	-101	+3	15.5	16.5	0.02	1.1
Freescale	MC13212	2005	2-3.4	-92	+3	37	30	1	7-20
Jennic	JN5139	2007	2.2-3.6	-95	+0.5	37	37	2.8	>2.5
TI	CC2420 CC2520	2003 2008	2.1-3.6 1.8-3.8	-95 -98	-20 to 0 -20 to 5	18.8 18.5	17.4 25.8	1 0.03	0.58 0.5

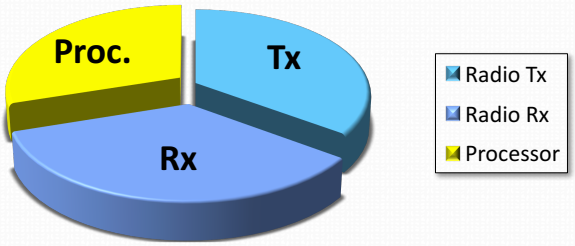
#50mW

24

Typical energy budget (WSN node)

- What are the main sources of energy consumption ?
  - Radio: 5-50mW
  - Processing: 1-20mW
  - Sensors



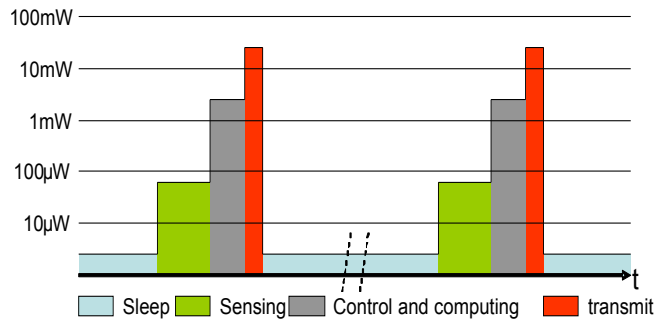


25

WSN power consumption profiles

- Four different modes
  - Sleep (leakage current)
  - Sense
  - Control compute
  - Transmit receive

Protocol State	Energy
Send/Receive BEACON	50µJ
Data Transmission	80µJ
Data Reception	100µJ
Sleep (30ms)	**2300µJ**



Autonomous nodes?

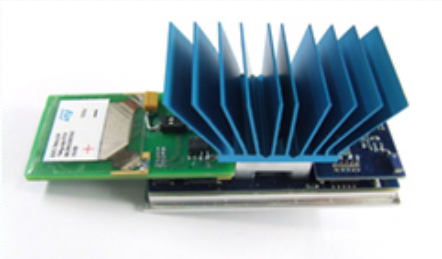
- A WSN node is limited by the total energy it can store or scavenge from the environment
  - Need a drastic reduction in the total consumed energy (radio + processing)

Energy Source	Characteristics	Efficiency	Harvested Power
Light	Outdoor Indoor	10~24%	100 mW/cm^2 **100 μW/cm^2**
Thermal	Human Industrial	~0.1% ~3%	**60 μW/cm^2** ~1-10 mW/cm^2
Vibration	~Hz–human ~kHz–machines	25~50%	~4 μW/cm^3 ~800 μW/cm^3
RF	GSM 900 MHz WiFi	~50%	0.1 μW/cm^2 0.001 μW/cm^2

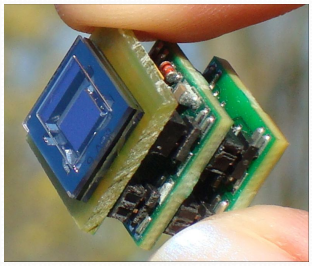
27

Energy Harvesting

- STMicroelectronics
  - Thermogenerator, solid-state thin-film battery, 2.4 GHz wireless link



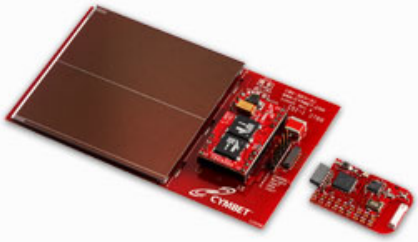
- IMEC
  - Vibration harvesting by MEMS piezoelectric power generation



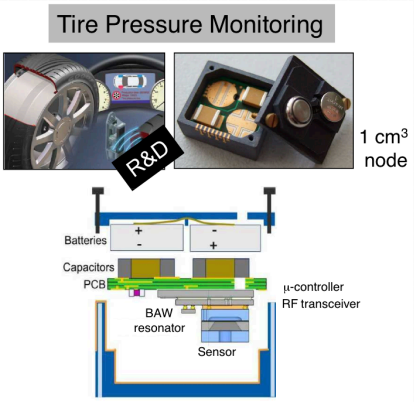
28

Energy Harvesting

- TI/Cymbet
  - Solar and in-door light harvesting with photo-voltaic (PV) cells, thin-film rechargeable battery



- Infineon
  - Vibration harvesting

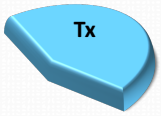


29

Objectives for Energy Reduction

- *How can we design an energy-efficient platform for wireless sensor networks ?*
  - *Platform = software + hardware + protocols*

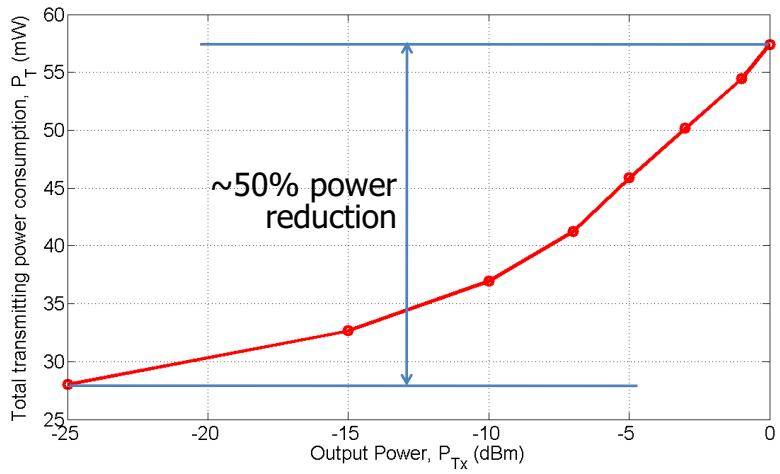
- (1) Decrease transmission (Tx) power
  - Power-aware signal processing
  - Error detection and correction



30

TI/Chipcon Radio Transceivers

- CC2420 radio transceiver: $P_T(P_{Tx})$

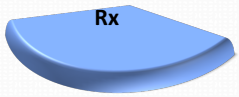


31

Objectives for Energy Reduction

- *How can we design an energy-efficient platform for wireless sensor networks ?*
  - *Platform = software + hardware + protocols*

- (2) Optimize radio activity (MAC layer)
  - Avoid idle listening and overhearing
  - Wake-up interval tuning
  - Synchronization?



32

Objectives for Energy Reduction

- *How can we design an energy-efficient platform for wireless sensor networks ?*
  - *Platform = software + hardware + protocols*

- (3) Power optimization of the hardware
  - Dynamic power management
  - Ultra low-power sleep modes
  - Optimize hardware and software
  - Co-processing

33

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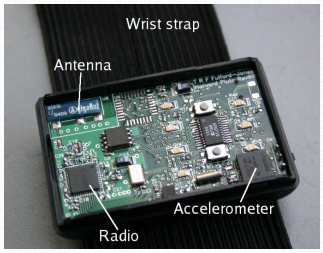
Examples of sensor nodes and networks

- Academic
- Start-up companies

- Activity Sensors, Pulse Oximeter
- ECG, EEG

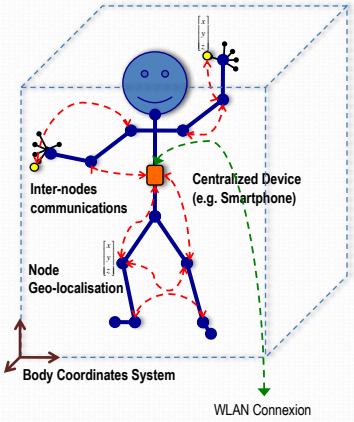
Activity Sensors

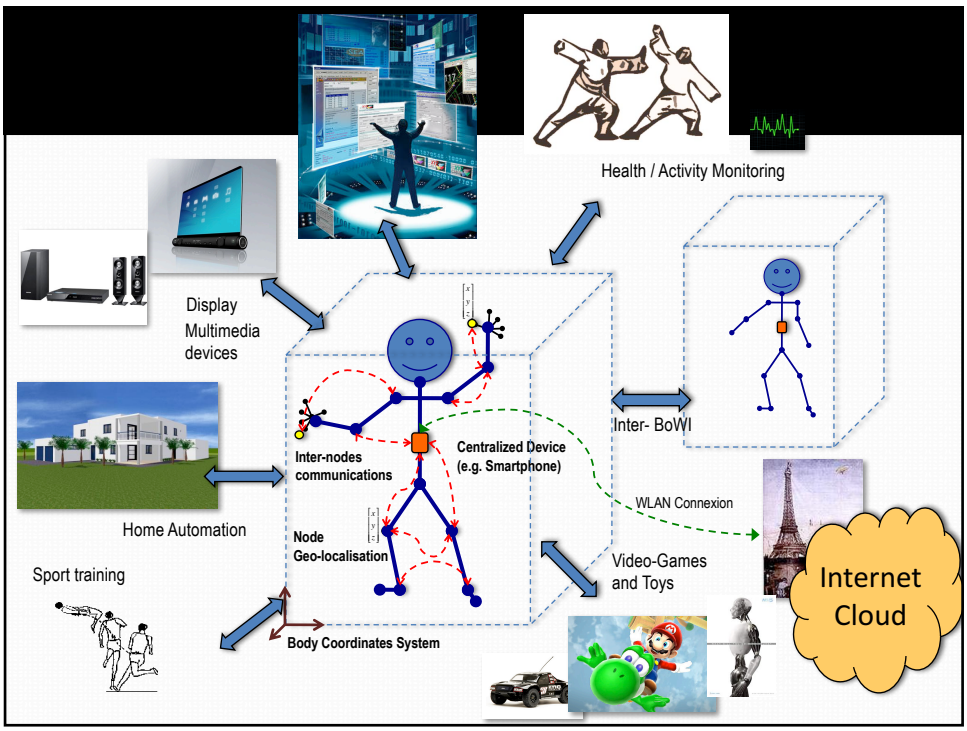
- Useful in monitoring patients undergoing physical rehabilitation such as after a stroke
- Pluto custom wearable (Harvard): TI MSP430, ChipCon CC 2420 radio
- 5 hours on a rechargeable 120 mAh lithium battery
- Mini-B USB connector for programming and battery recharge
- Software runs under TinyOS



Body-World Interaction: Context

- Explore new Body / World interfaces through **Wireless Body Sensor Networks**
- New wireless, low cost & wearable solutions for **posture and gesture recognition**
  - In- or out-door, everyday environment, **without additional equipment**
  - Ultimately **low power**: energy harvesting (200µW)





Prototypes

- Zyggie Platform
  - Motion capture with wireless BAN sensors
  - Data set for simulation
  - Algorithm validation

Zyggie V1

BAN sensors

Avatar motion on Android tablet

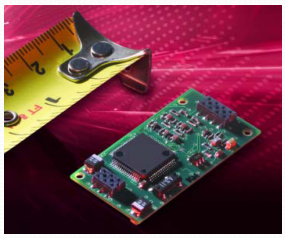
- Zyggie V2
  - UWB for enhanced positioning
  - Cortex M4 for local processing

Pulse Oximeter

- Non-invasive technology used to measure the heart rate (HR) and blood oxygen saturation (SpO2)
- The technology used is to project infrared and near-infrared light through blood vessels near the skin
  - By detecting the amount of light absorbed by hemoglobin in the blood at two different wavelengths the level of oxygen can be measured
  - The heart rate can also be measured since blood vessels contract and expand with the patient's pulse which affects the pattern of light absorbed over time
- Computation of HR and SpO2 from the light transmission waveforms can be performed using standard DSP algorithms

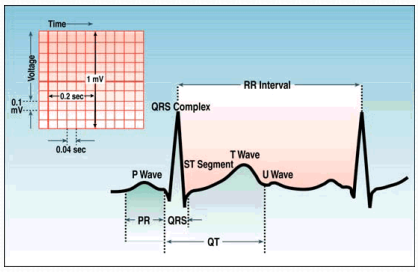
Pulse Oximeter

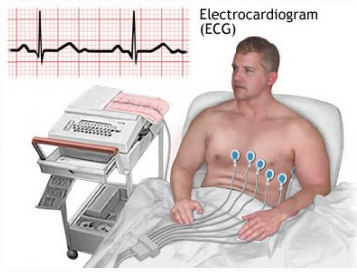
- Smiths Micro Power Oximeter Board
  - Length: 39 mm
    Width: 20 mm
    Height: 5.6 mm
  - 6.6 mA at 3.3 V, typical power: 22 mW
  - Pulse range: 30-254 bpm
    SpO2: 0 to 99%
  - Data is transmitted from the oximeter board at a rate of 60 packets per second (5 bytes per packet)



- Minolta Pulsox-2
  - Size: W69xH60xD28 mm
  - Weight: approx. 70g (with 2 AAA batteries)

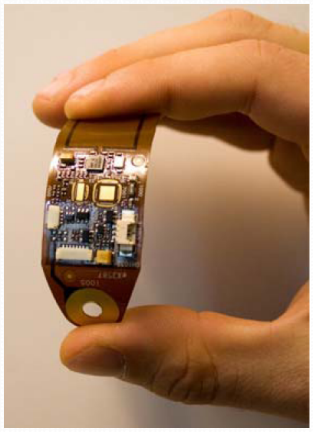
Electrocardiogram Signals





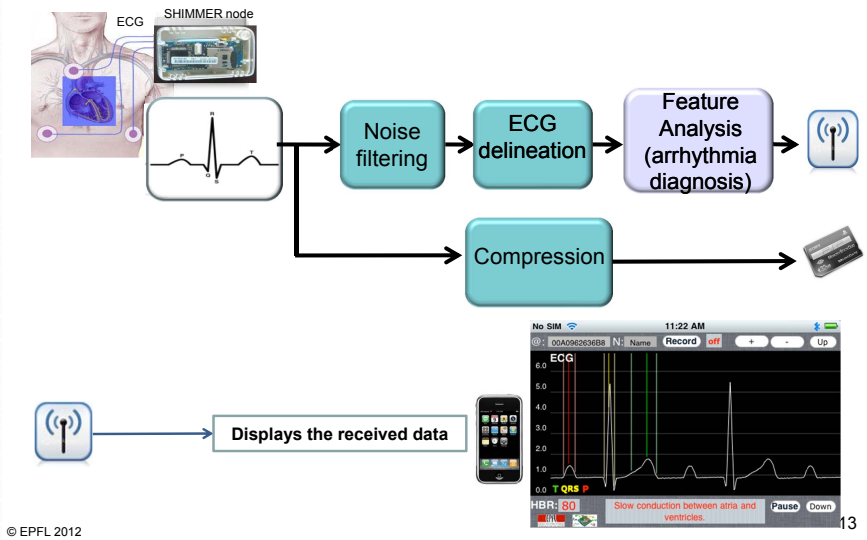
- The P wave is associated with the contractions of the atria (the two chambers in the heart that receive blood from outside)
- The QRS is a series of waves associated with ventricular contractions (the ventricles are the two major pumping chambers in the heart)
- The T and U waves follow the ventricular contractions

Electrocardiograph (EKG)

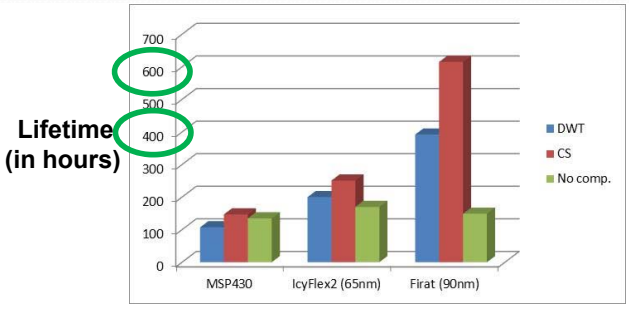


- IMEC has recently developed a wireless, flexible, stretchable EKG patch for continuous cardiac monitoring
- Placed on the arm or on the leg the same system can be used to monitor muscle activity (EMG)
- 2.4 GHz radio link, miniaturized rechargeable lithium-ion battery
- Total size is 60x20 mm2
- Data is sampled between 250 and 1000 Hz an continuously transmitted
- Battery has a capacity of 175 mAh which provides for continuous monitoring from one day to several days

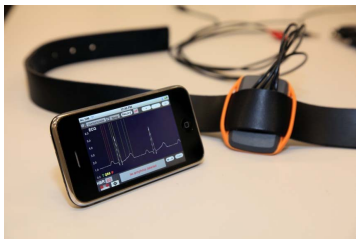
ECG Compressed Sampling



ECG Compressed Sampling

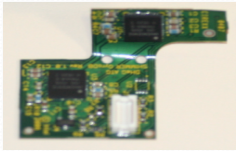


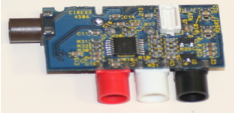
- Feasible to develop long-lasting smart WBSN nodes that interact with smartphones
  - Adapts at run-time to patient's heart
  - Automatic detection of arrhythmias
  - Real-time notification to doctors



SHIMMER Hardware Platform

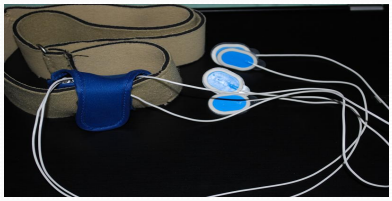
- SHIMMER
  - Long battery life
  - Tri-axial accelerometer
  - SD card slot for data storage
  - Bluetooth or 802.15.4 radio
  - Programmable processor (MSP430)
  - 20-pin extension header
  - 20-internal and external modules: ECG, EMG, GSR, etc.
  - TinyOS component based embedded operating system





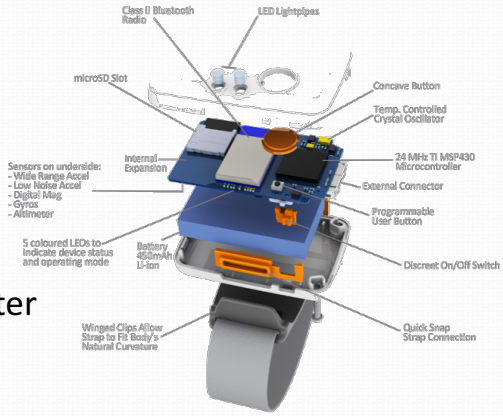
SHIMMER

- SHIMMER straps
  - Custom-made neoprine straps were fabricated to affix the SHIMMERs to the body
  - One strap used for the wrist and a larger one for the chest



SHIMMER

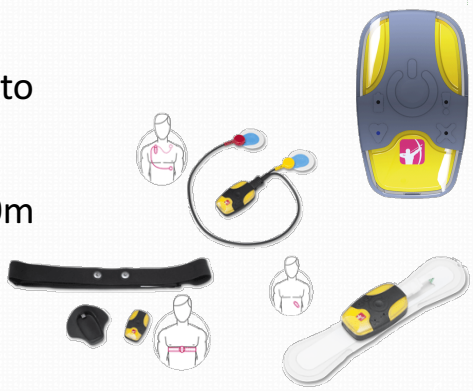
- Shimmer2
  - MSP430 up to 8MHz
  - TinyOS
- Shimmer3
  - Tri-axial gyroscope
  - Tri-axial magnetometer
  - MSP430 24MHz microprocessor
  - C-programming



ECG Pulse@Care

- Sampling 3-way ECG up to 1000Hz
- HRV (Heart Rate Variability): Sampling@1000Hz
- Accelerometers 3D up to 400Hz
- Wireless Bluetooth transmission up to 100m
- Storage: 20-30 days, 24/24
- Body Temperature

PULS@CARE
Biosignal Analysis Everywhere

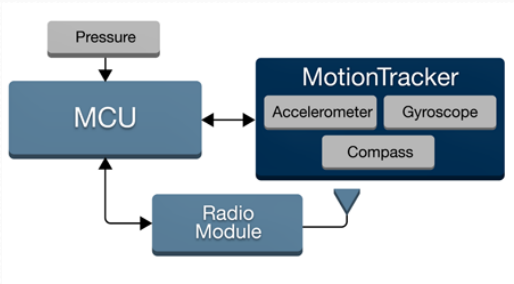


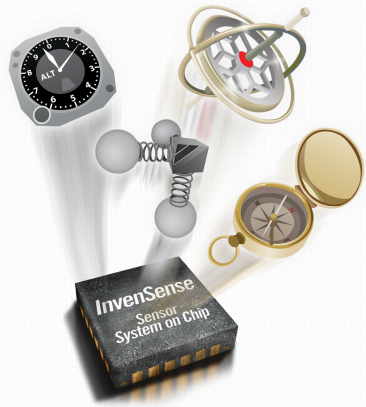
http://www.megaemg.com

49

Movea/InvenSense

- World's smallest and highest-integration 6-axis and 9-axis solutions

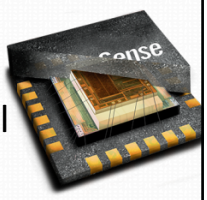




50

InvenSense Sensors

- World's smallest and highest-integration 6-axis and 9-axis solutions
  - MEMS gyroscope, accelerometer, and compass (for 9-axis) with on-board Digital Motion Processor (DMP)
- Embedded MotionApps software solution with advanced calibration and APIs for high performance and faster time to market
- Integrated electronics for complete signal conditioning
- Lower power consumption by processing MotionFusion™ on-chip and not on MCU



51

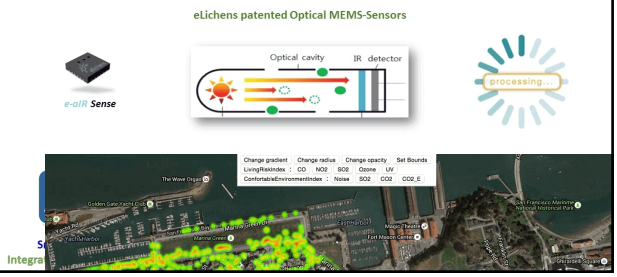
InvenSense Positioning Everywhere

- Location and tracking technology improves accuracy outdoors and indoors by augmenting GNSS and Wi-Fi based location infrastructure
  - Inertial Navigation System (INS) allows usage between driving and/or walking
  - The device can be used in any orientation within the vehicle or on-person
  - World class INS error modeling for optimal navigation using MEMS
- Integration with GNSS, Wi-Fi and other absolute navigation systems

52

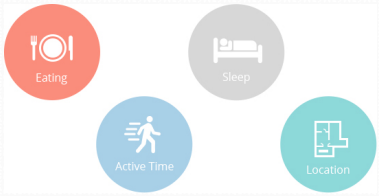
eLichens

- The lichens are air pollution bio-indicators,
- eLichens is the digital marker of air quality.
- Detect, monitor, coach and predict air quality
- Geo-localized Air Quality: millions of Pollution data Points now, tomorrow and everywhere
- Unique & Pate



CarePredict

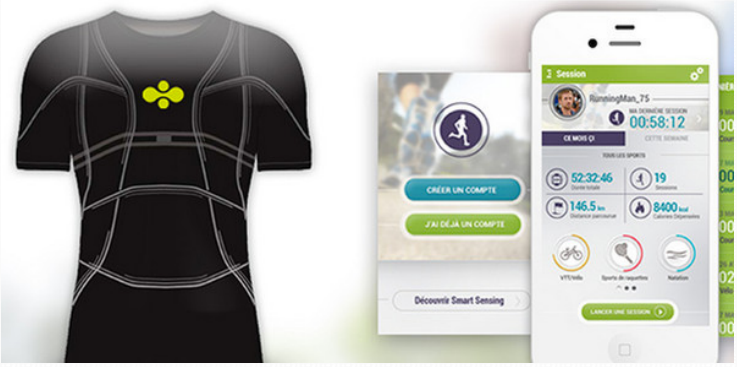
- Senior care: track changes in ordinary behavior
  - For example, a senior entering into a depressive phase will start having restless sleep patterns, loss of hygiene and changes in eating patterns several days before the episode
- Wearable that tracks their activities of daily living, from waking up, bathing, sleeping, quality of sleep, to brushing teeth, eating, drinking, cooking and more



54

CityzenSciences

- Smartclothing
  - Sensor-based smart fabric
  - Heart rate, GPS location, speed, heat, movement

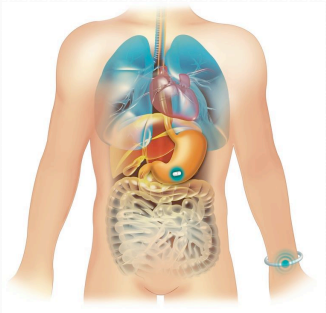


55

BodyCap

- Device, to be swallowed, allows a reliable and continuous measurement of gastro- intestinal temperature
  - e-Celsius pill

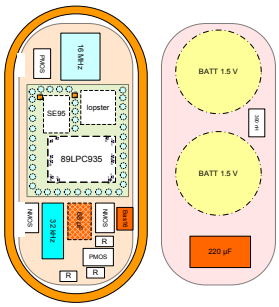
- Skills: miniaturisation of electronic devices, communication, embedded software and optimisation of energy management

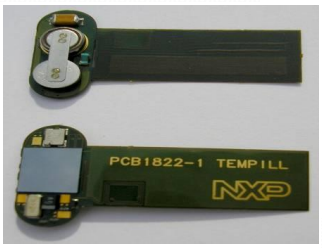


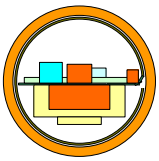
56

e-Celsius® pill

- Storage: Up to one year
- Weight: 1.7g
- Size: 17.7mm x 8.9 mm
- Sampling: 30s
- Accuracy: 0.2° C
- Stores up to 2000 data
- Wireless transmission: 433 MHz
- Communication: 1 m
- Operational duration: 20 days



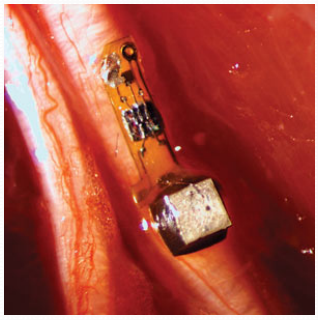




57

Towards Neural Dust

- Tiny ultrasound-powered motes could record and stimulate nerve activity
  - very low-power device, drawing only 0.12 milliwatt
- Challenge: Make the motes small enough to be embedded in the brain



You Sound Nervous: This tiny sensor, attached to a rat's nerve, is powered by ultrasound. Nerve signals change the way the device reflects ultrasound, and an external sensor can hear the change.

58