GENESI: long-lasting Green WSNs for structural health monitoring

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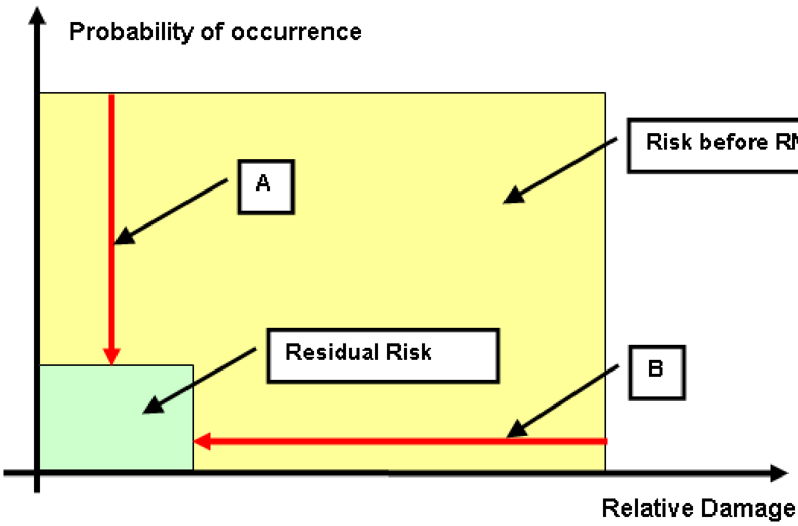
Structural Health Monitoring

- Structural health monitoring (SHM) in civil engineering is defined as the instrumentation of structures, including buildings, bridges, dams and highways with sensors, and accompanying equipment to assess structural integrity.
- The target is reducing risks and increasing safety of buildings and infrastructures. The risk can be defined as the product of amount of damage multiplied with the probability of occurrence.



Structural Health Monitoring

- Structural risk management therefore requires the following steps:
  - **Risk evaluation** summarizes possible damages associated to unwanted events (life losses, property damages, negative influence on schedule for construction, financial loss, damage to nature / to reputation etc.) Only recognised risks can be classified and handled. Handling risks normally results in a reduced damage in case of occurrence of the event.
  - **Risk probability** rates the possible occurrence of the listed risks.
  - **Risk classification** includes estimation of the probability of occurrence of a given event combined with the expected damage associated to the event.
  - **Risk handling** implies risk reduction to an acceptable level and elimination of unacceptable risks. It includes identifying in detail the monitoring strategy to be sure that possible risks are early detected and handled when no damage or little damages have occurred.

GENESI

- *GENESI will develop a new generation of large-scale, **heterogeneous**, **energy-efficient**, **situation-aware** wireless sensor networks for structural health monitoring and control which are able to **autonomously operate for several decades** perfoming **in situ reasoning** and evaluation of potential failures **invisible to current monitoring.***

GENESI's vision

- Enabling a new generation of green wireless sensor networks
  - energy harvesting
  - replacing batteries with fuel cells
  - reduce to the bare minimum energy consumption
    - ✓ protocols, algorithms, in network processing
    - ✓ radio triggering circuit (Wake-up radio)
- Solving problems which prevents WSN to be brought to the market
  - Reliability/fault tolerance/resiliency to interference
  - Ease deployment and management
    - ✓ tools
    - ✓ integration with existing middleware and applications for the selected application scenario
- Exploit cooperative sensing/operation
  - to reduce network load and energy consumption
  - to enrich context understanding
  - self-learning the context and obtaining operating adaptivity

} Structural Health Monitoring

Requirements-high level overview

- Requirements have been analyzed together with end users
  - SHM characterized by different phases (e.g. before the excavation, when excavation is close to sensor location, when it is far away but the sensor monitor area is still affected by excavation, long lasting monitoring after works have been completed)
    - ✓ each phase
      - Requires activation of different sets of sensors
      - With different frequency of readings
        - » typically low (one per hour-one every day)
      - Has different harvesting opportunities (e.g. in a tunnel during excavation there are little harvesting opportunities while wind harvesting can be very effective when underground is passing in the tunnel; in a bridge sensors have solar and wind harvesting opportunities during construction, also vibration when cars are passing on the bridge)
  - Phases duration, sets of sensors to attach to nodes (with different energy requirements), harvesting opportunities, other challenges (propagation environment, casing) depend on the specific application domain → **general system has to be customized and optimized for the specific setting**

Requirements

Monitoring tunnels

First phase: preliminary lining, excavation phase

Sensors	Load cell	Strain gauge
Sensors per instrumented section	2	1-2 pairs
Distances between instrumented sections	50 – 100 meters depending on the type of terrain	
Sampling rate	Hour/Day dependig on the distance of the excavation face from the instrumented section	
Latency	Minutes	

Requirements

Monitoring tunnels

Second phase: final lining, long term monitoring

Sensors	Strain gauge	Piezometer	Borehole rod extensometer
Number of sensors per instrumented section	10	1 to 6	12
Distances between instrumented sections	100 meters	300 meters	
Sampling rate	2-4 times at day	Days	
Latency	Minutes		

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Requirements

Waste management / landfills

Sensors	Sampling rate		Latency	
	Normal	Critical	Normal	Critical
Typical sensors				
Pressure meters (water/gas/rock pressures)	Day	Hours	Day/week	Minutes
Extensometers	Day	Hours	Day/week	Minutes
Thermometers	Day	Hours	Day/week	Minutes
Precipitation	Day	Hours	Day/week	Minutes
Additional sensors				
Soil moisture	Day	Hours	Day/week	Minutes
pH meter	Day	Hours	Day/week	Minutes
Water/gas flow	Hour/minute	Minutes	Hours/day	Seconds
Number of sensors	More than 50 sensors (extension up to several hundreds meters)			
Expected lifetime	From years to decades			

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System desirable features—by end users

- Transparent
  - Should not affect construction operations (cost up to 100K euros a day)
- Long lasting
  - To monitor ideally the site as long as it will last
- Reliable
  - Reliable communication also in challenging modes of operations such as during excavation
  - Also in presence of interference from other technologies operating on the same frequency band
- Topology requirements in general are quite loose
  - Some sensors have to be placed in specific positions but extra sensors can be placed for relay purposes in many possible locations at very limited cost and with little effort

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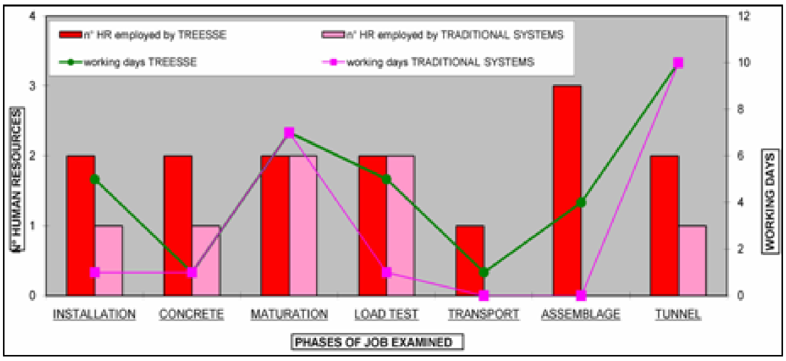
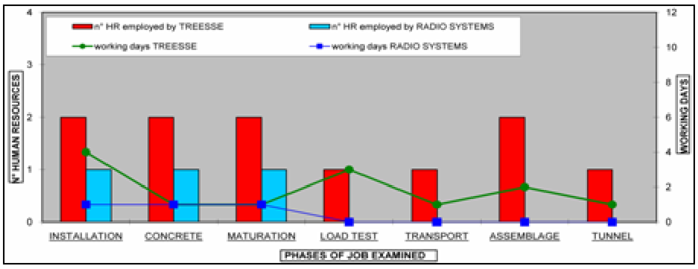
A simple example: Advantages of a cable-less system



Number of human resources devoted to maintenance and repair of a traditional system (pink) out of the total number of people involved in deploying and supervise a structural health monitoring system (red). This histogram has been drawn from data of our end-users Consorzio Tre Esse. The data are typical of real-life ordinary operations of existing systems



Human resources devoted to maintenance and repair of a GENESI radio-based system

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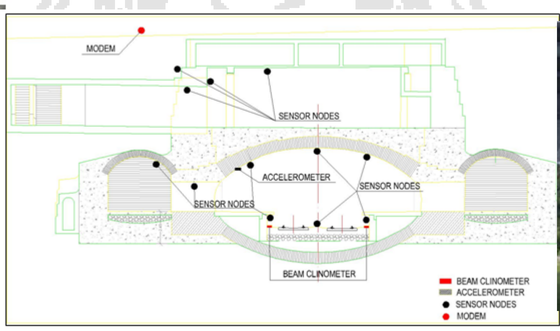
GENESI experimental activities

- Monitoring of a tunnel under construction
- Each monitoring section is constituted by 2 or 3 concrete segments equipped with 6 strain gauges with vibrating string.

- Monitoring of the metro station Colosseo
- Existing station
- Continous monitoring, during excavations under the metro station, real time data communication

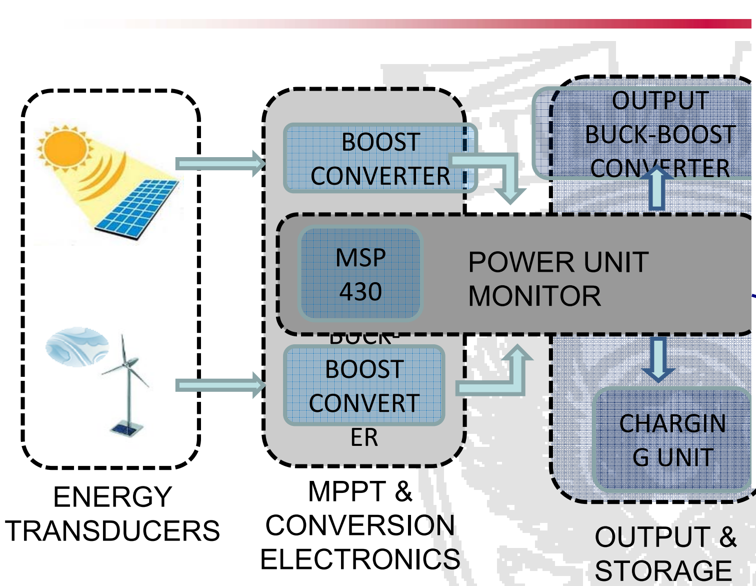
- Monitoring during construction of the Poya Bridge in Switzerland

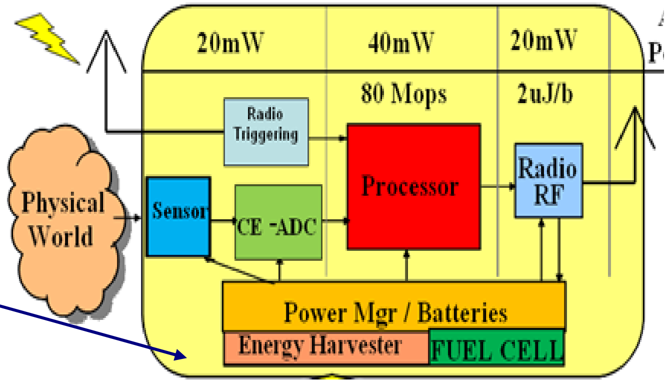


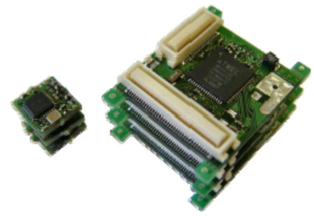
•Max scale: 100 nodes, no cables

•Challenges: hostile environment, ‘infinite lifetime’, real-time data communication, resilient to failures and interference

GENESI Solution







•Key technologies: low power small factor fuel cell (ST), multi-source Harvester (UniBo), radio triggering capabilities (UOR)

•Communication protocols and algorithms exploiting these novel HW feature (UOR, UTwente, Tyndall)

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GENESI platforms

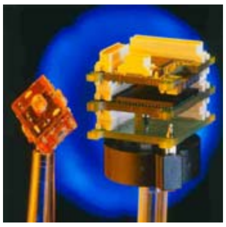
- TinyOs compliant
- Radios both in the 2.4GHz and in the 400/800MHz band
- Standard interfaces
- Two platforms:
  - EvoNode (design based on UOR requirements by a local company)
  - Tyndall Nodes (Tyndall)

NOT developed within GENESI, used and customized for SHM in GENESI

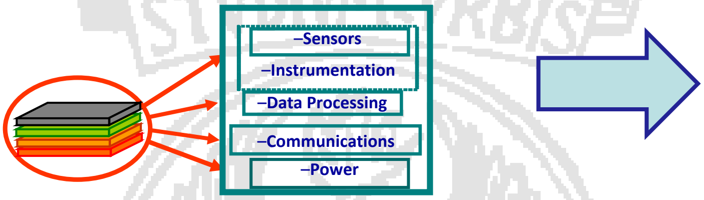
EvoNode

Evonode 1030	
Processor	MSP430F5438
CPU	RISC - 16 bit
Program Flash Memory	256KB
RAM	16KB
EEPROM	512B
ADC	12 bit
Serial Communications	USB, UART
RF Transceiver	CC2520
Frequency	2.4 GHz
Transmit data rate	250 kbps
Receiver sensitivity	-98 dBm
RF power (max)	5 dBm
Adjacent channel rejection	
+ 5 MHz channel spacing	49 dB
- 5 MHz channel spacing	49 dB
Serial Memory Flash	M25P32
Memory	4MB
Battery	2X AA
Configuration and programming	by USB connector
Sensor features	Temperature, Humidity

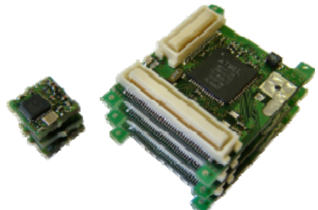
Tyndall node Capabilities



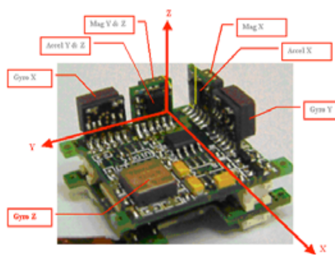
The Tyndall Modular Platform Configuration



Tyndall Mote



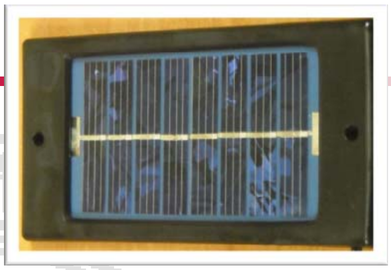
10 mm and 25 mm Solutions

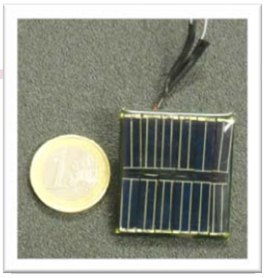


Inertial Measurement Unit

- The Tyndall WSN team has key competencies in the areas of:
  (1) Miniaturised Heterogeneous RF System Integration, Sensor Development and Deployment
  (2) Embedded Software, Protocol Development and Sensor Fusion.
- State of the art Modular, Heterogeneous Prototyping Platform for distributed ad-hoc WSN.
- Features: Modular, Flexible, Reconfigurable, Scalable, Robust, Expandable.
- To date upwards of 40 modular layers have been developed including:
  - Bluetooth, Zigbee 802.15.4, 433/868/915 MHZ, GPS
  - Over 20 sensor layers including Inertial Measurement

Harvesting-Photovoltaic Path UOB





- **115x67 mm pv module**
  - Max power voltage: 3.3 V
  - Current @ MPP: 150 mA

- **F.O.C. MPPT algorithm →**

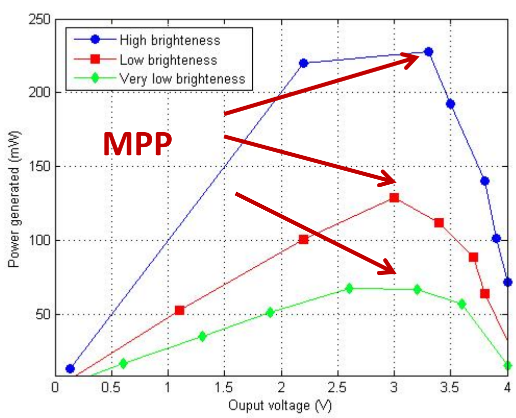
$$V_{MPP} \approx V_{OC} * K_{FOC}$$

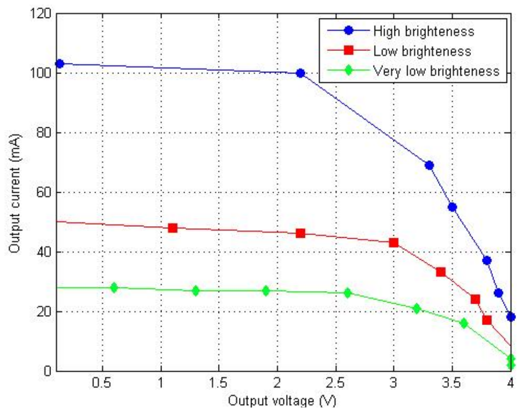
  - Proportional constant K_{FOC} belongs to interval 0.70÷0.75
  - Small PV pilot cell to obtain open circuit voltage V_{OC}
  - Software routine for main and pilot cell voltage acquisition, V_{MPP} estimation and boost switching signal regulation
  - Efficiency ≅ 80%

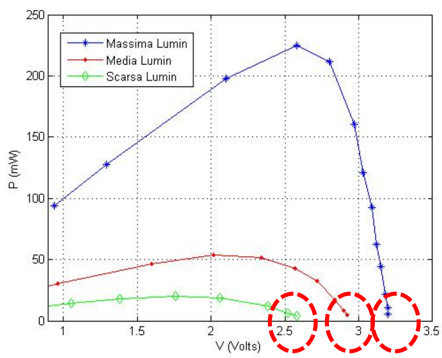
PV Cell – Maximum Power Point Tracking

Main Cell: Voltage - Power

Pilot Cell: Voltage – Power







- Main cell MMP value derived by pilot cell open circuit voltage
- Microcontroller-based mpp algorithm dinamically evaluates new MPP and adjusts main cell operating voltage

Air Flow Path

- **Plastic four-bladed Horizontal Axis Wind Turbine (HAWT)**
  - 63 mm diameter, 75 mm length
  - ~ 8 mW power output at 15 Km/h wind speed
  - Optimal load resistance value belongs to interval 550Ω÷715Ω
- **MPPT circuitry**
  - Buck-Boost PWM switching regulator operated in Fixed Frequency Discontinuous Current Mode

  - The converter shows the equivalent resistance given by microcontroller-generated PWM switching signal

$$R_{IN,eq} = \frac{2LT}{(DT)^2}$$

  - Efficiency ≅ 87%

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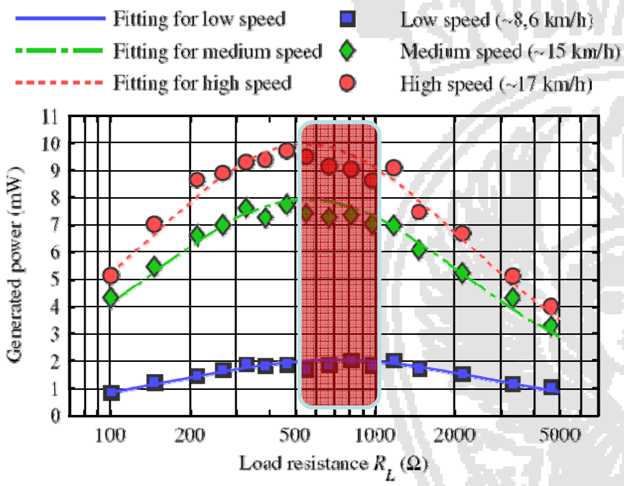
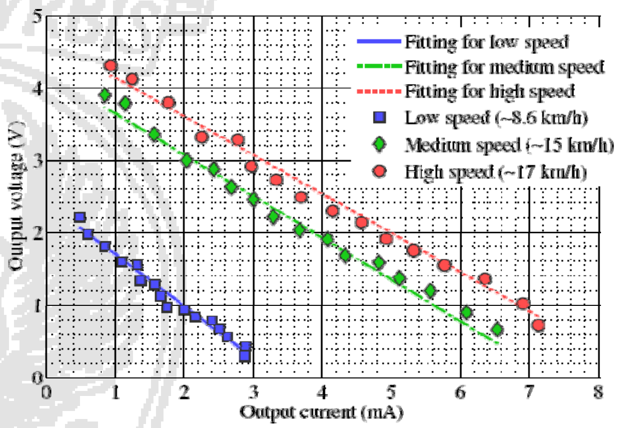
Wind Generator – Maximum Power Point Tracking

Power – load resistance



- 8 mW @ 15 Km/h
- R_L around 600 Ω maximizes power generation, for all the tested wind speeds

Load voltage – load current



- Optimal value: R_L = 550 Ω

Perfect dynamic impedance matching could only provide 2% more power

Fuel Cell

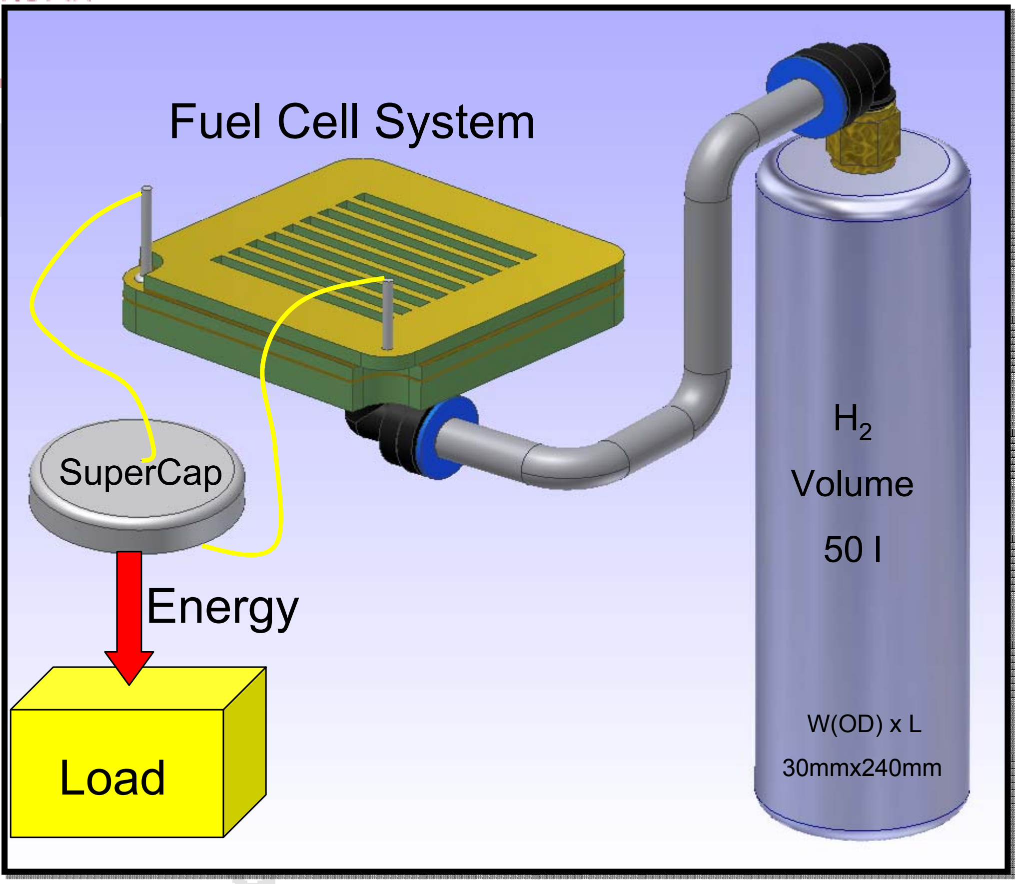
Hybrid System Implementation:

- Metal Hydride Storage H_2 Tank
- Fuel Cell System
- Battery
- Load

H_2 Volume	Electric Load	Endurance*
l	W	h
50	1μW	~5e7
50	1 mW	~ 50.000
50	10 mW	~ 5.000
50	100 mW	~ 500
50	1 W	~ 50
50	10 W	~ 5

*Electric Equivalence of H_2 Flow: 5.54 ml/min W

*Fuel Cell Efficiency: 30%



Radio Triggering Circuit (UOR)

- "Galena radio" approach
  - Limited power consumption
  - Compatibility with Zigbee protocol TX's
  - Scalable in term of number of nodes and performance
  - Board level Demo in Genesi
  - Chip (or MCM) in future
- Current status:
  - Matlab level system simulation in progress
  - Design of key component to allow PG with low power consumption

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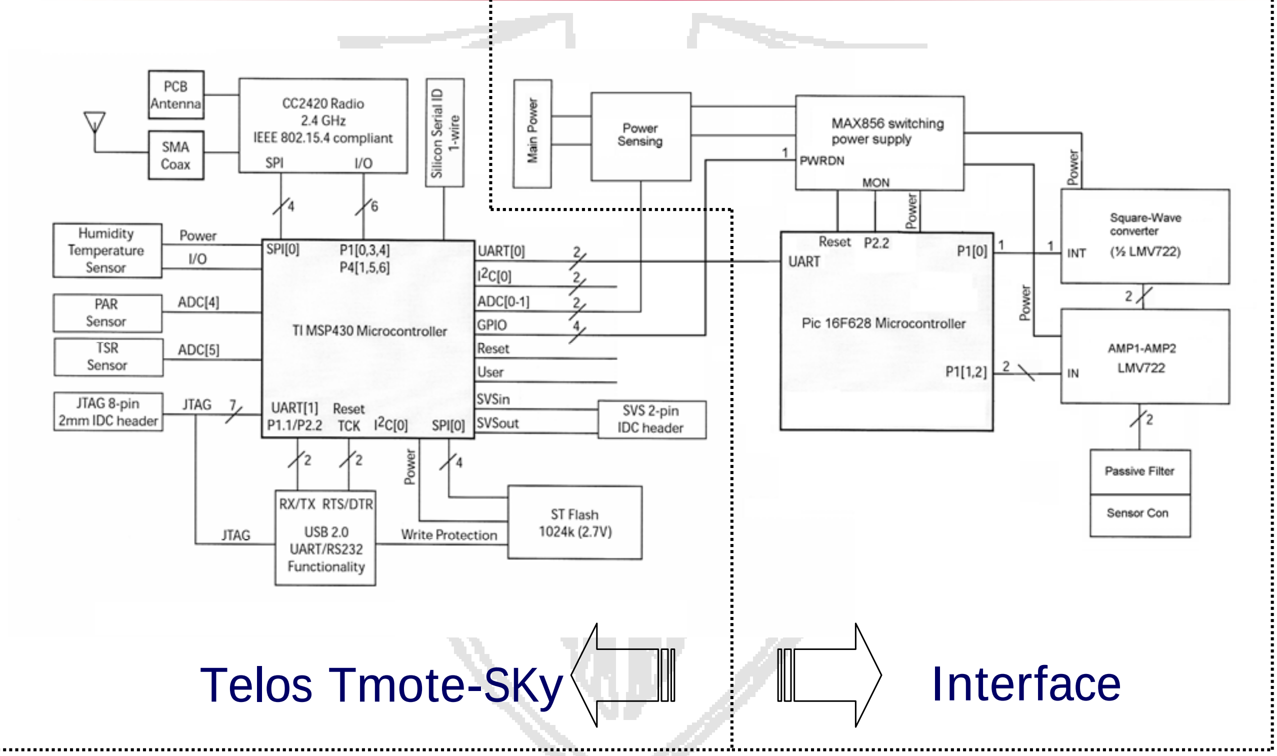
Interfaces with sensors (UOR&Treesse)



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Improved Interface with sensors (UOR)

- Improved interface
  - 6 mechanical sensor input lines
  - Wide power supply voltage range (CP approach) (1.5 – 24V)
  - Improved analog sensor architecture (PLL based detection fundamental mode)
  - Improved analog sensor implementation (fixed current pulse amplitude) PAM amplitude
  - Sleep mode available
- Current status
  - Characterization in progress
  - Preliminary data are fine: no further improvements seem to be needed

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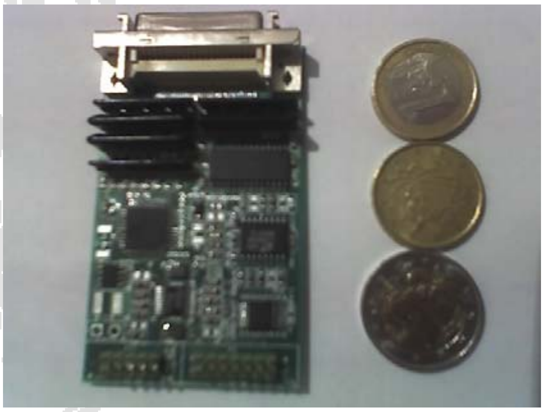
Improved Interface with sensors (UOR) 2



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Communication Protocols

- Design of novel protocol stack which account for (and are jointly optimized with) the design of the multi-source harvester and the radio triggering circuit
- Task allocation techniques to selectively activate sensors only upon need and to allocate sensing tasks to sensors over time accounting for node available energy, node expected available energy in the near future (which requires prediction models) and for the contribution each sensor can give to meet user needs

- Major problems related to interference from other technologies operating in the ISM band
  - especially WiFi
    - ✓ compromised completely WSN operations in our technology incubator
      - if channels are in use by WiFi there are little opportunities for WSN technologies
      - need to find (dinamically) best channels and be able to quickly switch over them
        - » Two approaches:
        - » Analytical. Model WiFi interference at high level, optimize WSNs operation
        - » Practical approach: design and test distributed schemes (accounting for theoretical results when completed)

- Thank you for your attention....