WSAN: Wireless Sensor and Actuator Networks

Overview of Power Processing Techniques for Harvesting-Based Wireless Sensor Nodes

July 5, 2013

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Power Electronics Group
http://pelgroup.dei.unipd.it/

DEI – Department of Information Engineering
University of Padova

The WSAN Strategic Project @ DEI

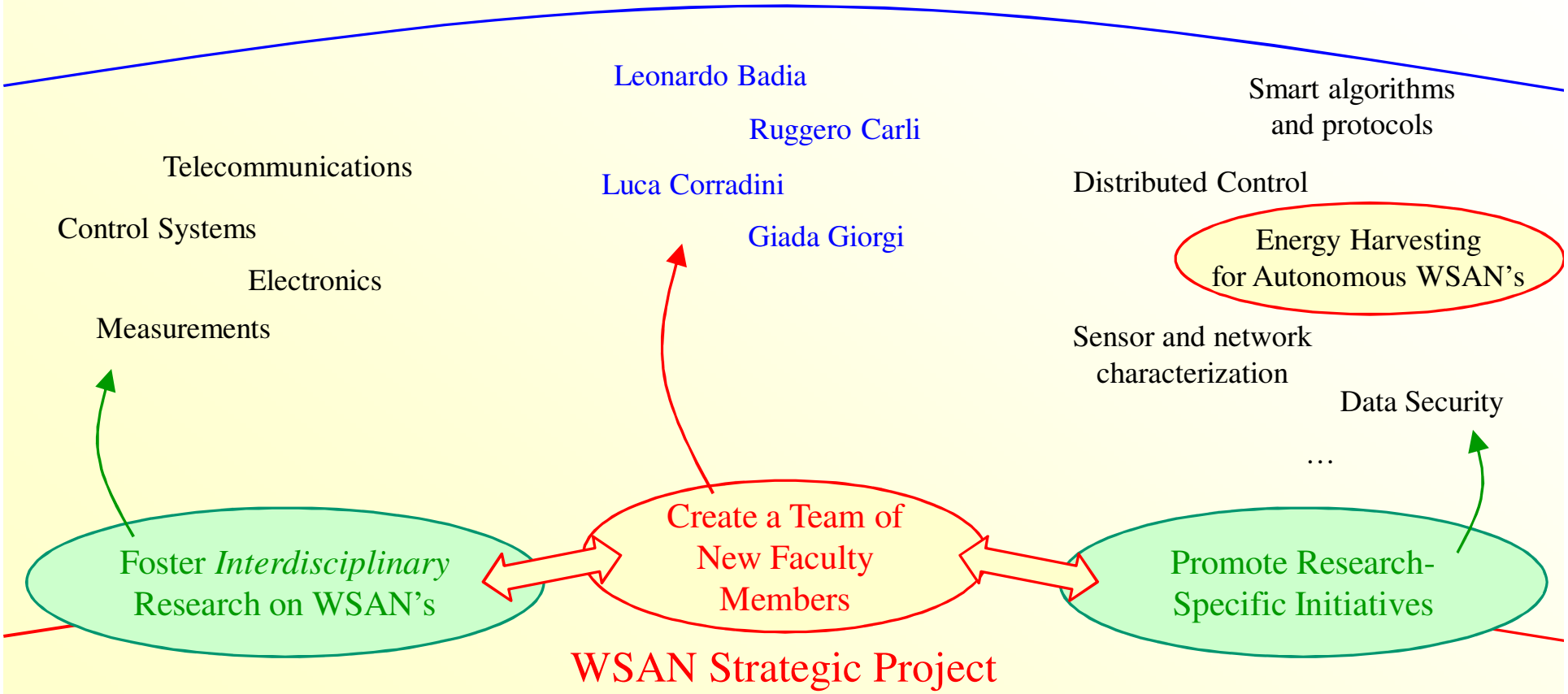
- Department-wide Strategic Project tackling open research and deployment issues of Wireless Sensor and Actuator Networks

- Joint proposal of the Telecommunication, Control Systems, Power Electronics and Measurements research groups
  - Main proponents:
    - Michele Zorzi (Project coordinator) — Full Professor of Telecommunications
    - Carlo Narduzzi — Full Professor of Instrumentation and Measurements
    - Giorgio Spiazzi — Associate Professor of Power Electronics
    - Sandro Zampieri — Full Professor of Control Systems

- Project kick-off in March 2011

The WSAN Strategic Project: Objectives

Long Term Objective:
Establish at DEI a Center of Excellence for Interdisciplinary Research on WSAN's



Workshop Focus:
WSAN Initiative in the Energy Harvesting Area

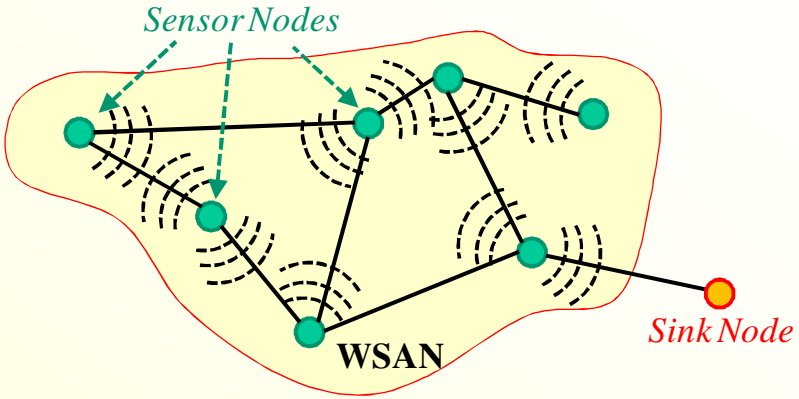
- **University-Funded Research Project** ("Progetto di Ricerca di Ateneo") started in 2012
  - Title: ***"Energy-Autonomous Wireless Sensor Networks: from Efficient Sensor-level Energy Harvesting to Intelligent Network-level Management"***

- Main proponents:
  - Luca Corradini — Assistant Prof., Power Electronics (Project coordinator)
  - Leonardo Badia — Assistant Prof., Telecommunications
  - Ruggero Carli — Assistant Prof., Control Systems
  - Giada Giorgi — Assistant Prof., Instrumentation and Measurements

- + Collaboration with University of Udine:
  - Stefano Saggini — Assistant Prof., Power Electronics

Energy Harvesting Project: Motivations

- Function of a WSAN:
  - Sense and sample a scalar field (Temperature, pressure, humidity, motion, vibration, etc…)
  - Route sensed information to a central unit or *sink node*



- Large WSAN's: tens to hundreds of nodes
- Practical deployment of large-scale WSAN's implies:
  - Zero-maintainance nodes ("Fit and forget" philosophy)
  - Prolonged sensor lifetime (e.g. > 2 years)
  - Low $/Wh

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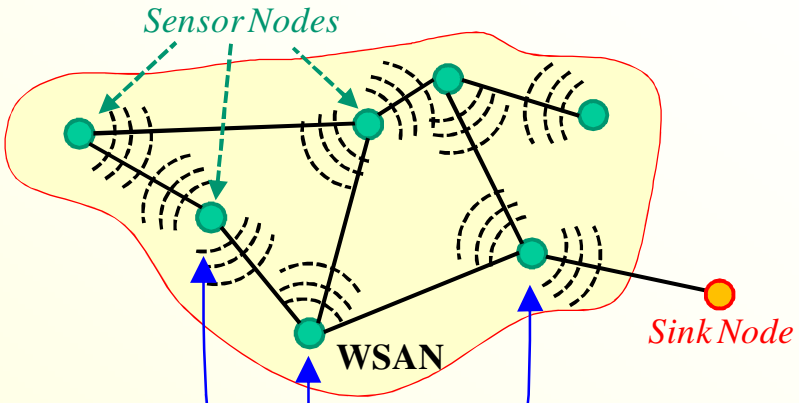

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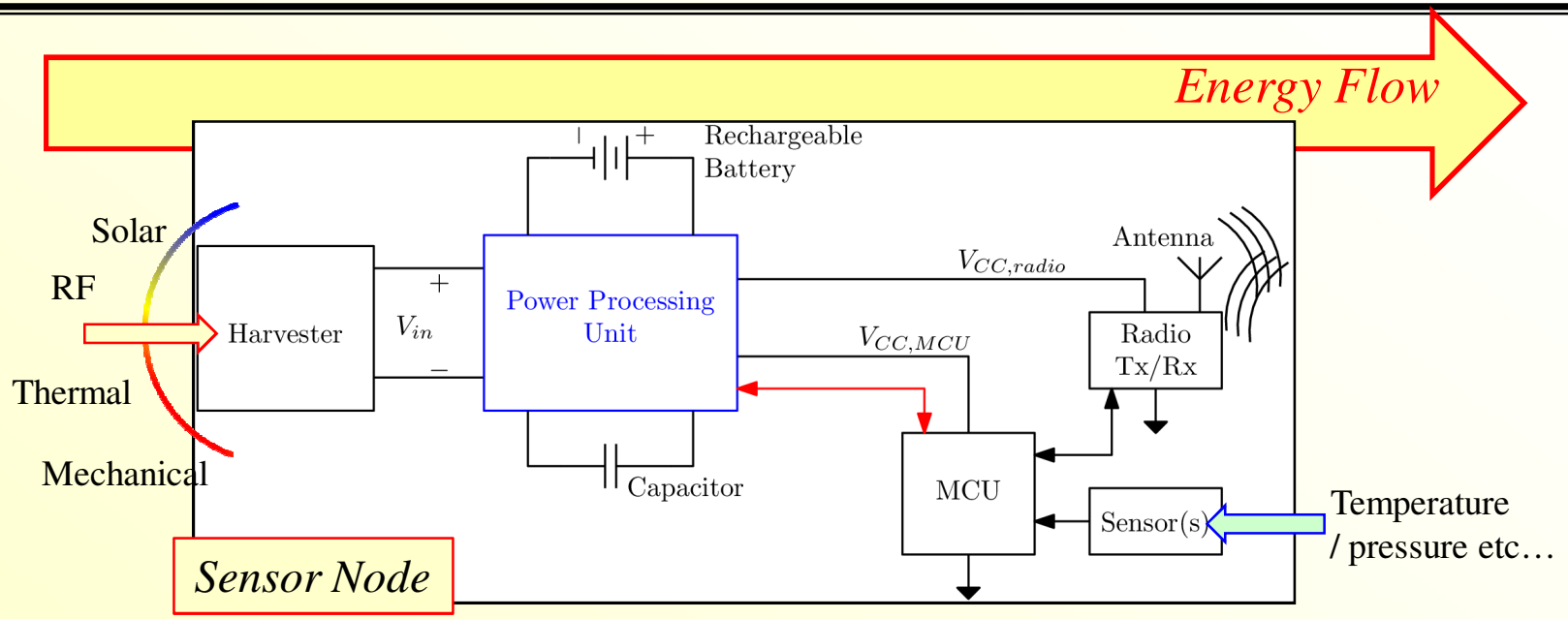
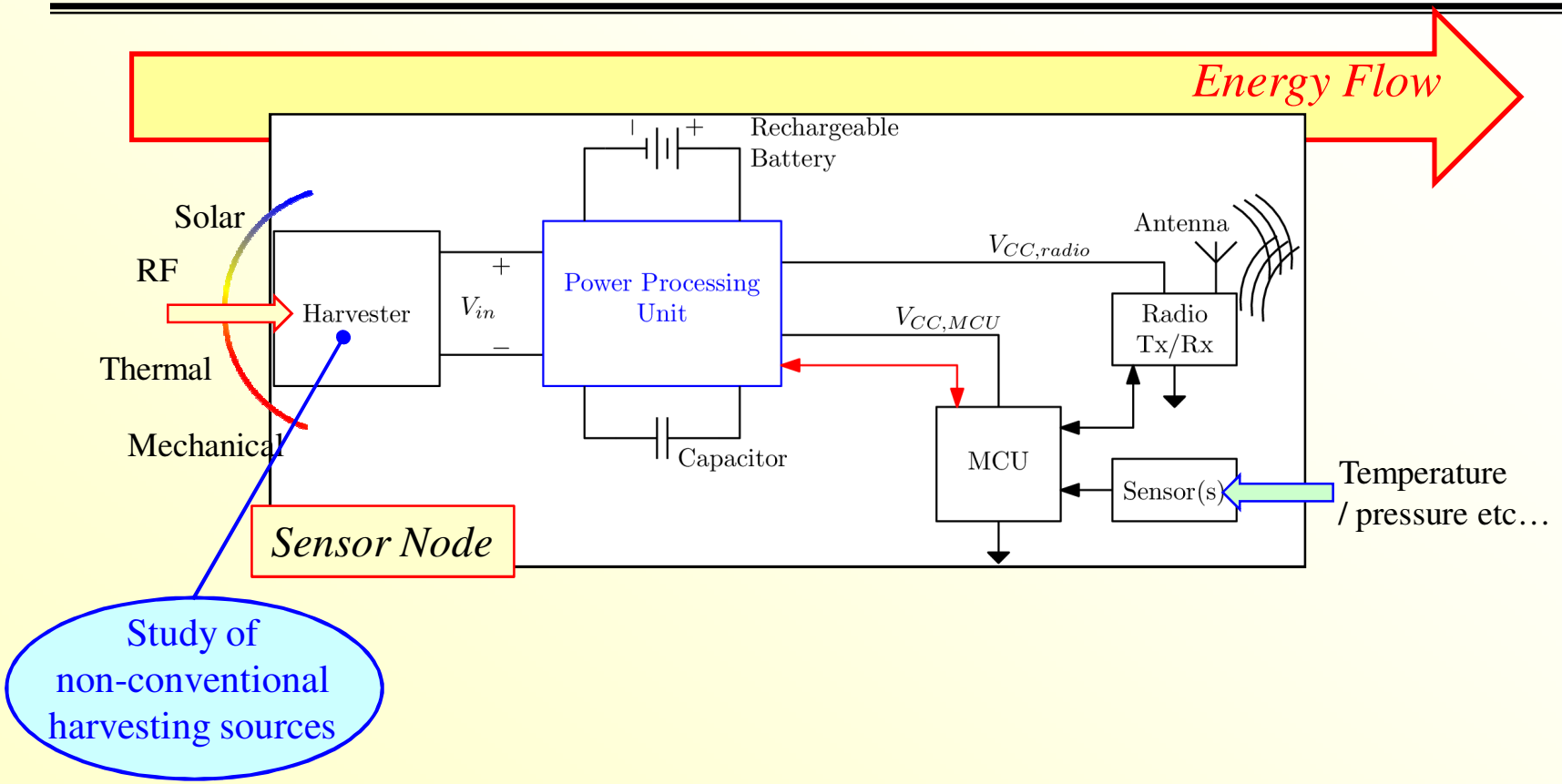
Research Trend:
Embed **energy harvesting capabilities** into each sensor node

The Harvesting-Based Wireless Sensor



- Energy Harvesting:
  - Absorb and locally store ambient energy from various sources
  - Large energy available at a very small rate ➔ Low power (tens of mW or less, depending on the source)
- Harvesting-Based Wireless Sensor – Building Blocks:
  - Energy harvester
  - Storage units: secondary (rechargeable) battery, capacitor
  - Power Processing Unit: source matching and storage management
  - Sensor loads: Microcontroller Unit (MCU), Transceiver, Sensor(s)

Energy Harvesting Project: Activities and To-Date Published Results



- F. Ongaro, S. Saggini, L. Corradini, "Low-Power Energy Harvester for Wiegand Transducers," in *Proc. 28th IEEE Applied Power Electronics Conference and Exposition* (APEC 2013)
- S. Saggini, F. Ongaro, L. Corradini, A. Affanni, "Low-Power Energy Harvesting Solutions for Wiegand Transducers," *to be presented at the 8th Energy Harvesting Workshop* (EHW 2013), Hannover, Germany

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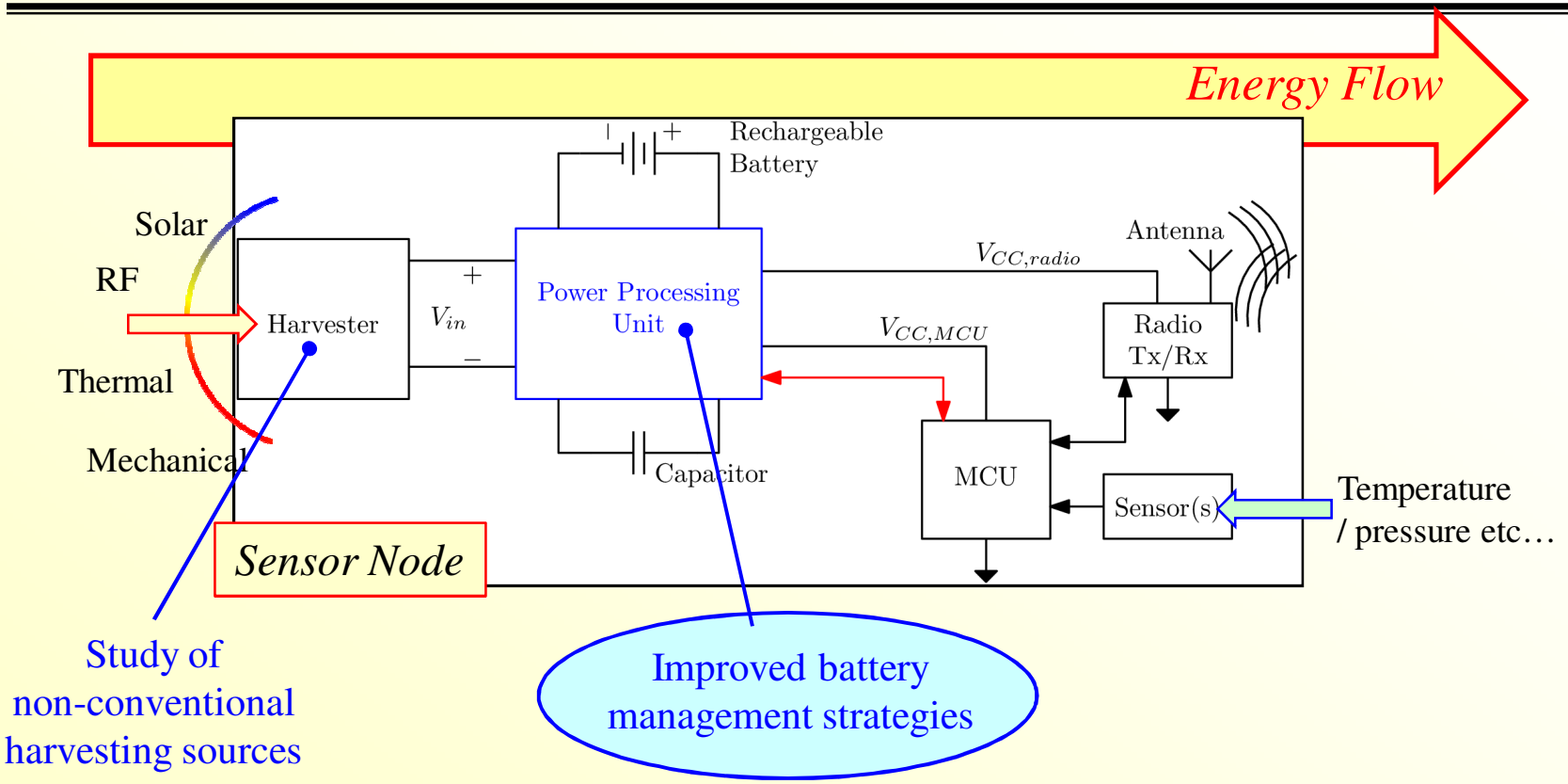

- G. Giorgi, A. Veronese, L. Corradini, "A Method for Estimating State of Charge in Energy-Aware Wireless Sensor Nodes," *to be presented at the 19th IMEKO TC-4 Symposium Measurements of Electrical Quantities* (IMEKO 2013)

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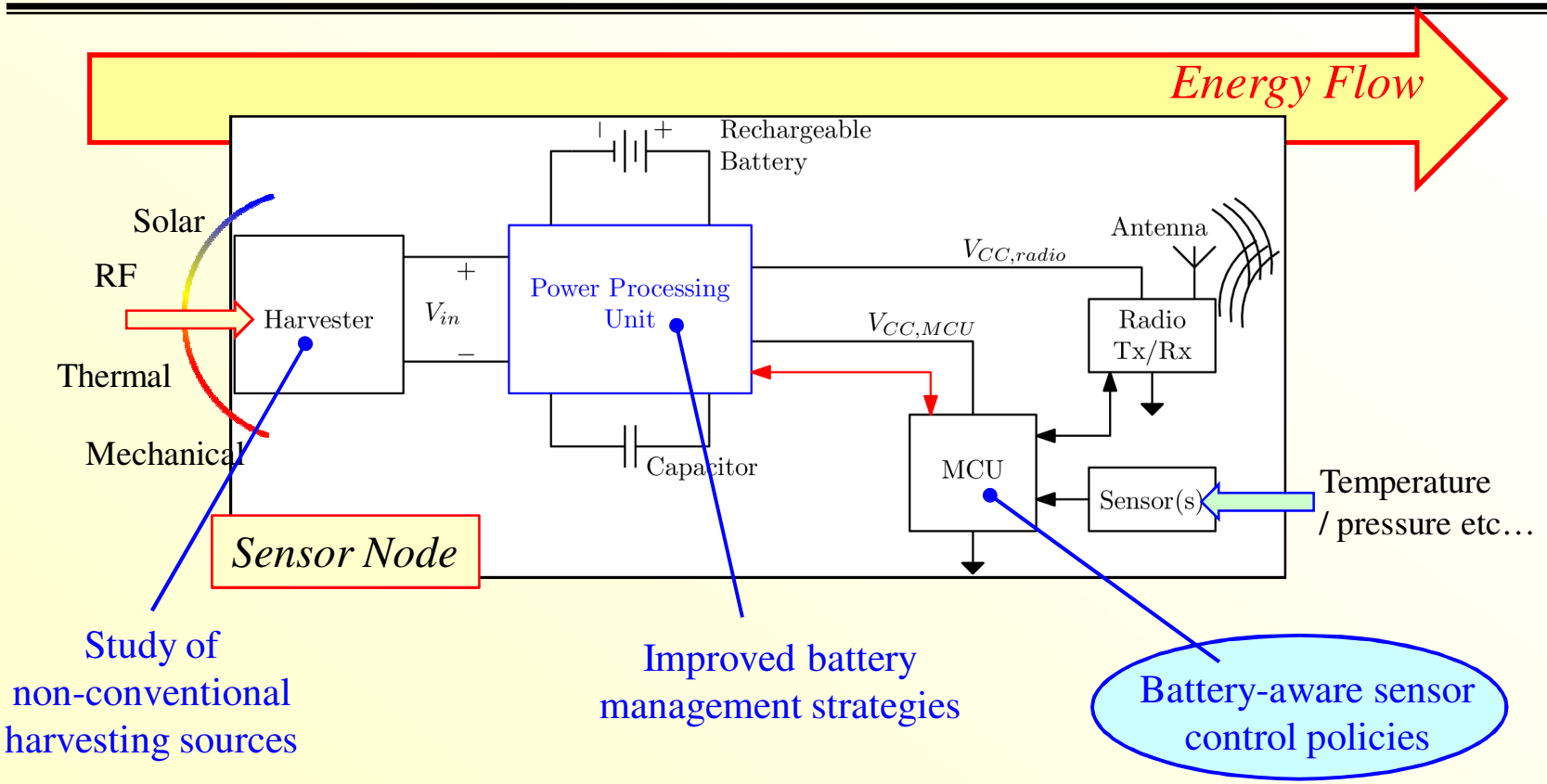
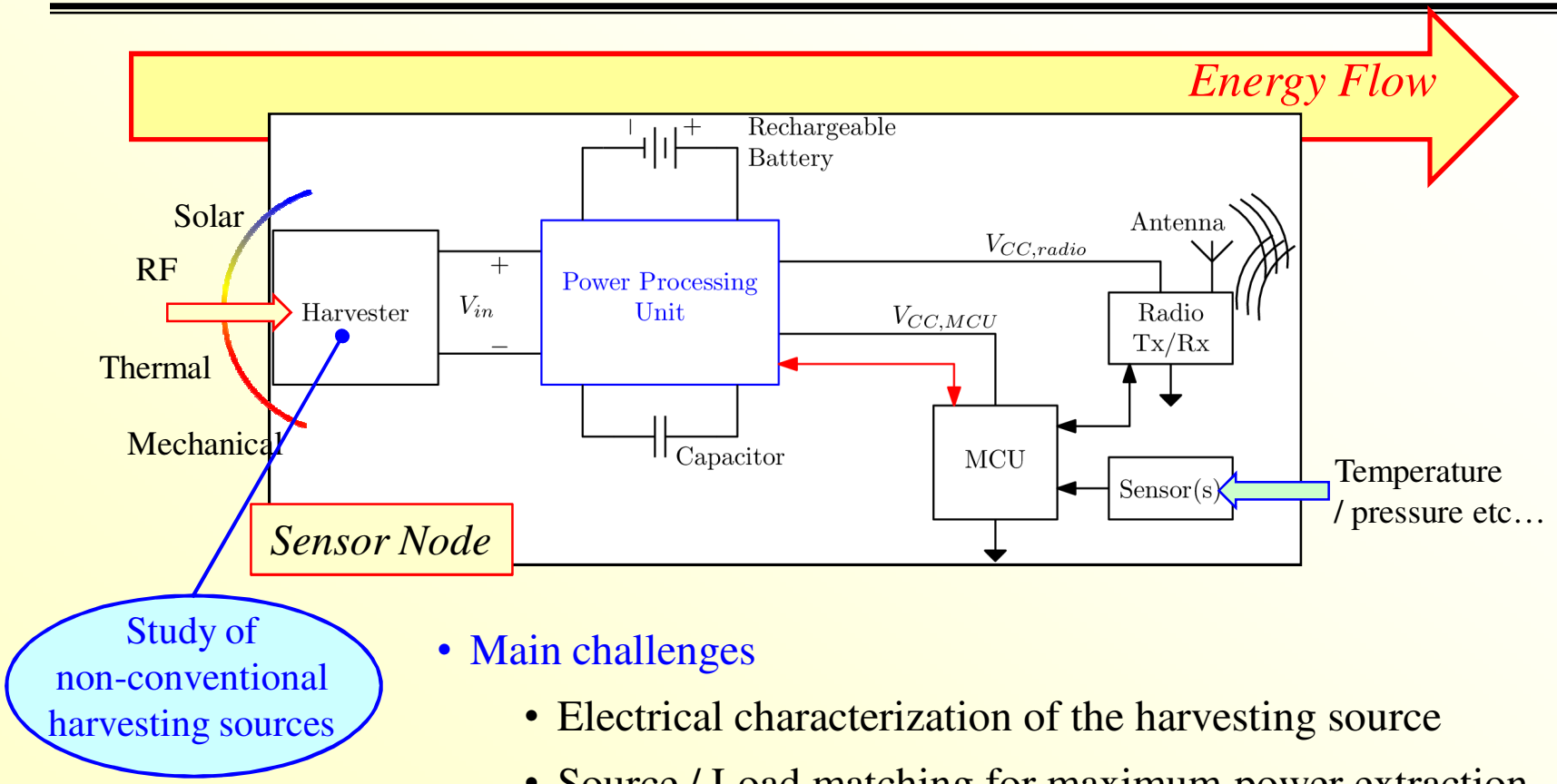


- N. Michelusi, L. Badia, R. Carli, K. Stamatiou, and M. Zorzi, "Correlated energy generation and imperfect State-of-Charge knowledge in energy harvesting devices," in *Proc. 8th International Wireless Communications and Mobile Computing Conference* (IWCMC 2012)
- N. Michelusi, L. Badia, R. Carli, L. Corradini, M. Zorzi, "Impact of Battery Degradation on Optimal Management Policies of Harvesting-Based Wireless Sensor Devices," in *Proc. 32nd IEEE International Conference on Computer Communications* (INFOCOM 2013)

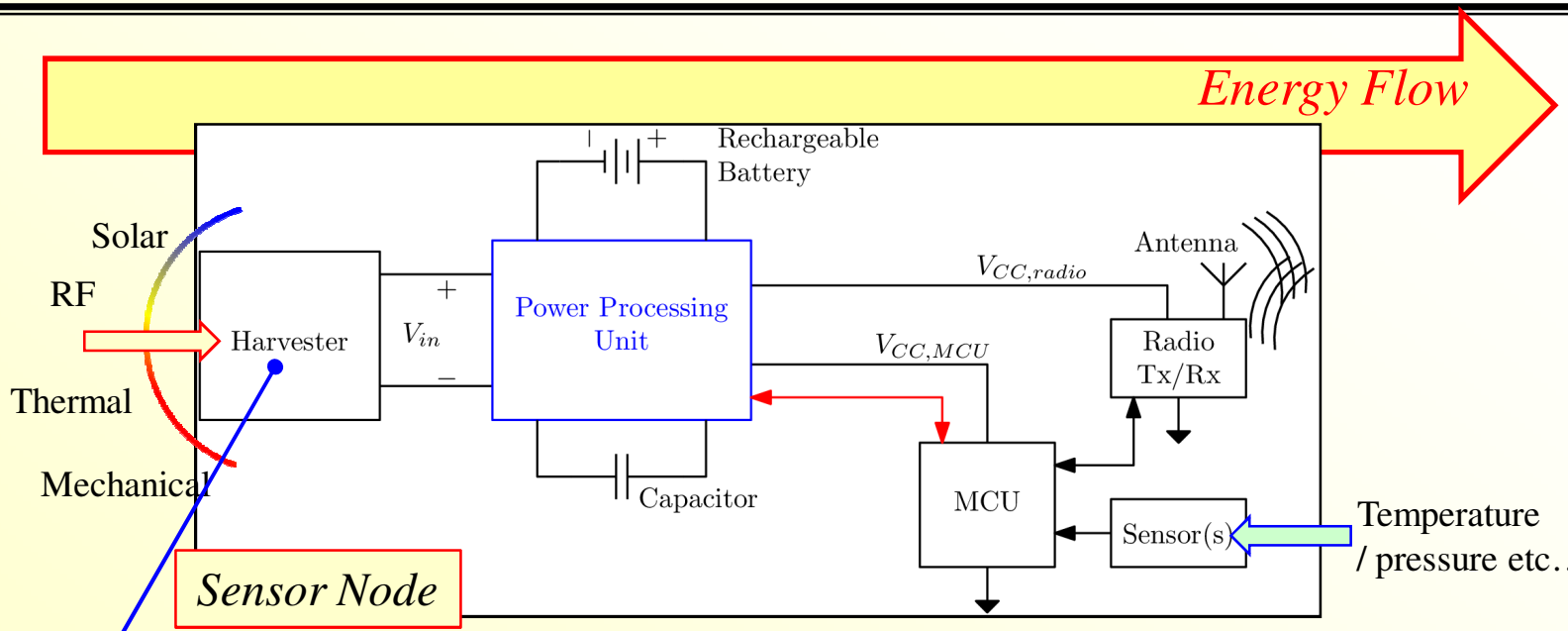
Energy Harvesting Project: Activities and To-Date Published Results



Study of non-conventional harvesting sources

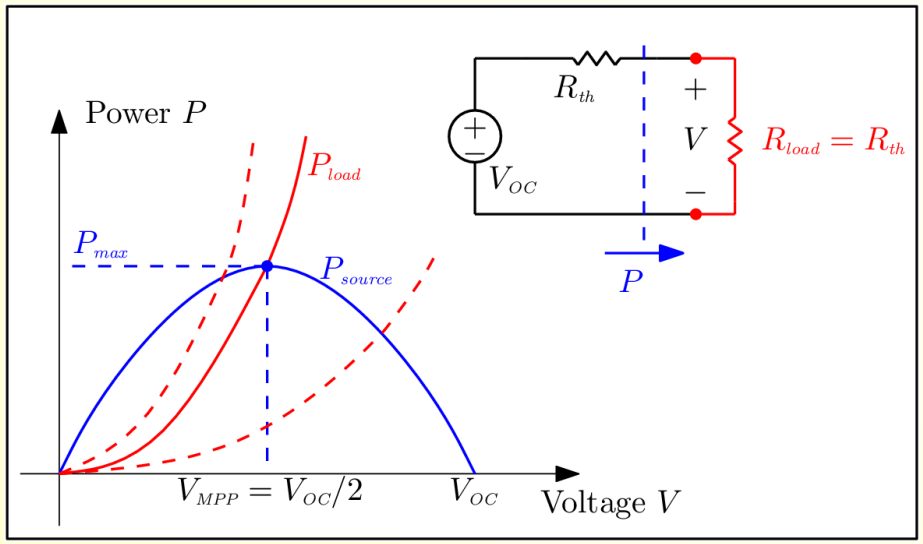
- Main challenges
  - Electrical characterization of the harvesting source
  - Source / Load matching for maximum power extraction

Energy Harvesting Project: Activities and To-Date Published Results



Study of non-conventional harvesting sources

Example:
Thévenin source ➔



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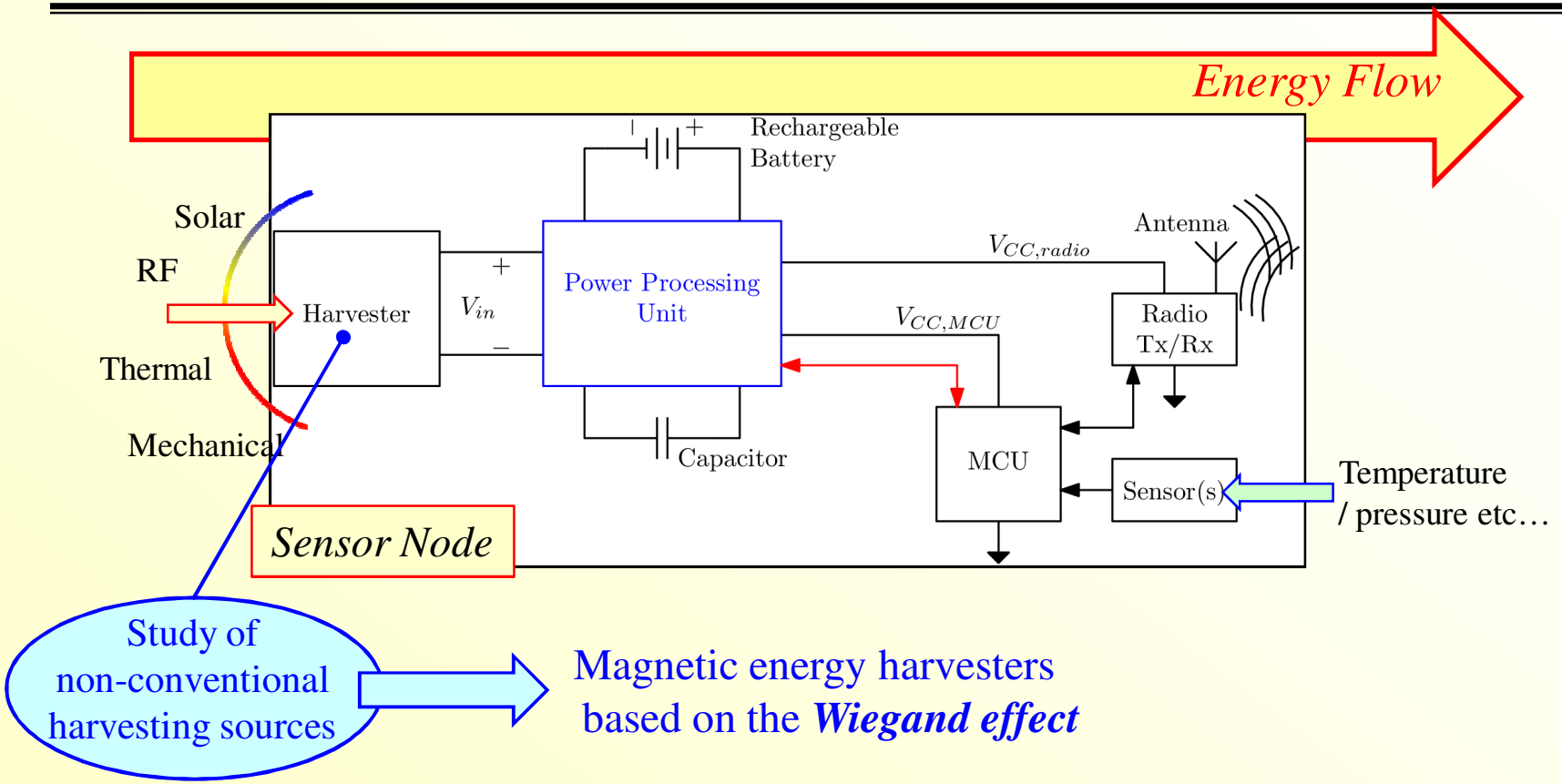


Study of non-conventional harvesting sources → Magnetic energy harvesters based on the ***Wiegand effect***

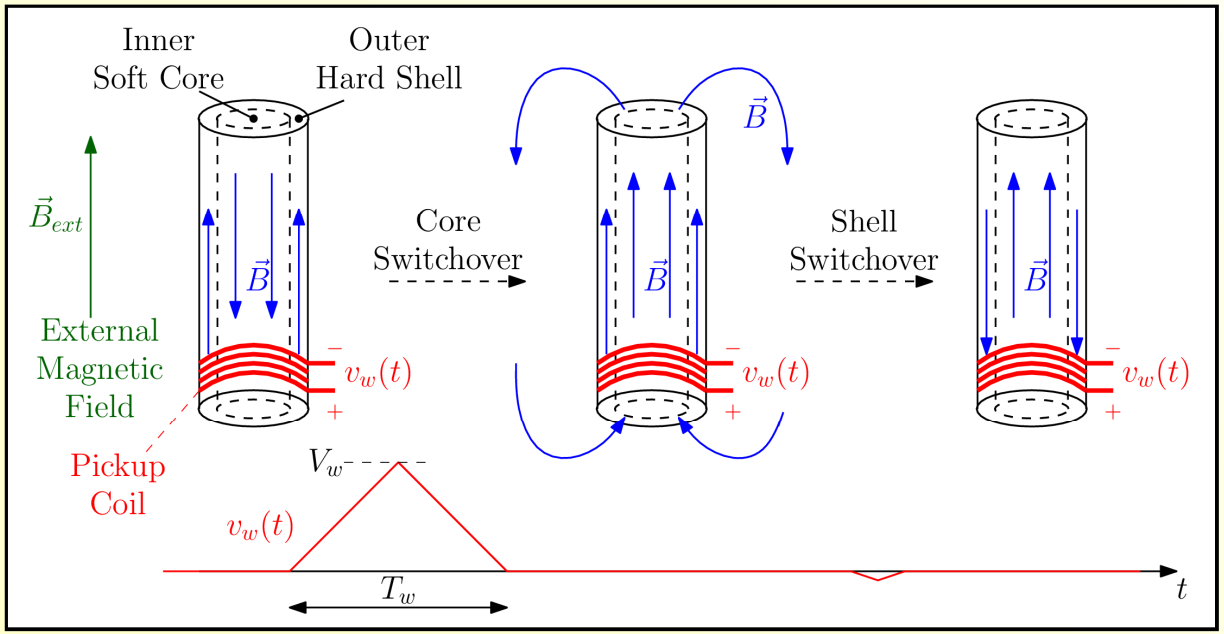
Low-Power Energy Harvesting Based on the Wiegand Effect

- **Wiegand Sensor:**

  - Coil wrapped around a ferromagnetic wire having non-uniform coercivity in the radial direction

  - Sharp magnetic hystheresis

    ➔ When interacting with a time-varying external magnetic field, it produces a voltage pulse which can deliver energy



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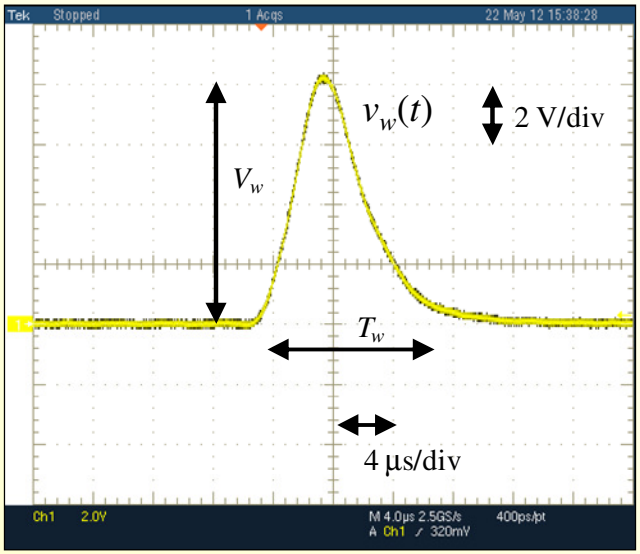
- Open-circuit voltage pulse of a commercial Wiegand sensor
  - $V_w \approx 8\text{V}$
  - $T_w \approx 10\ \mu\text{s}$



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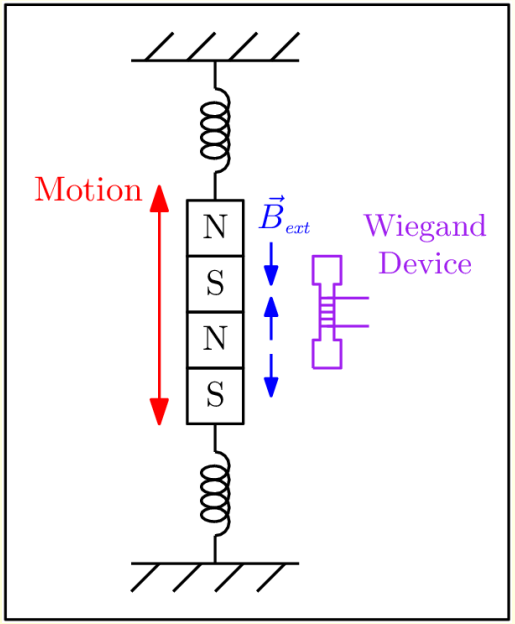
- Example: mechanical oscillator for Wiegand energy harvesting



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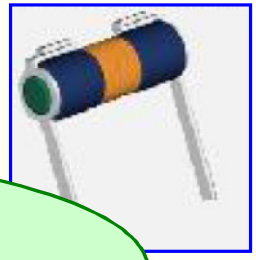
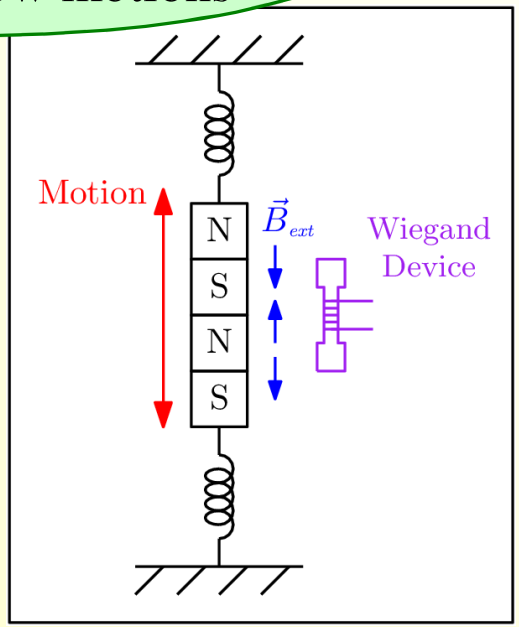


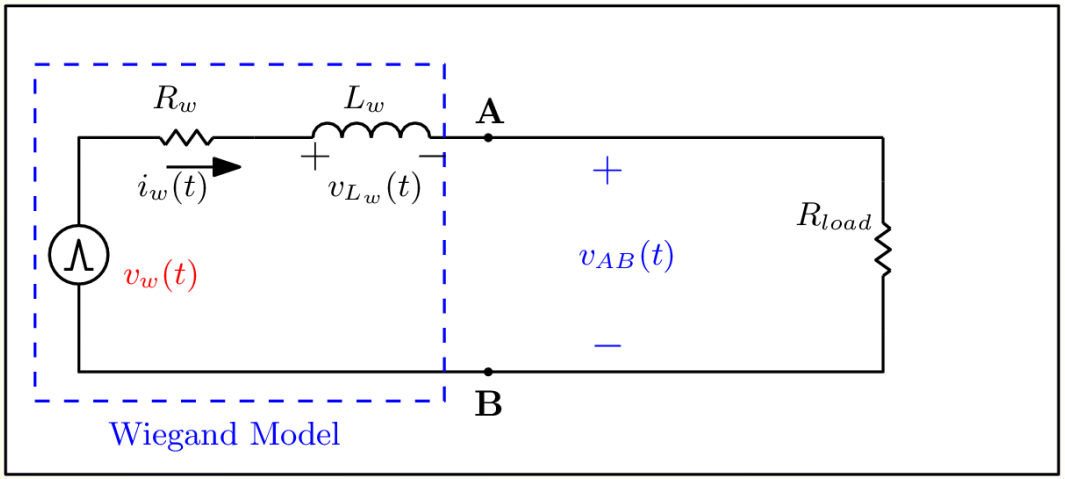
Advantage:
Energy is extracted even from very slow motions

- Example: mechanical oscillator for Wiegand energy harvesting

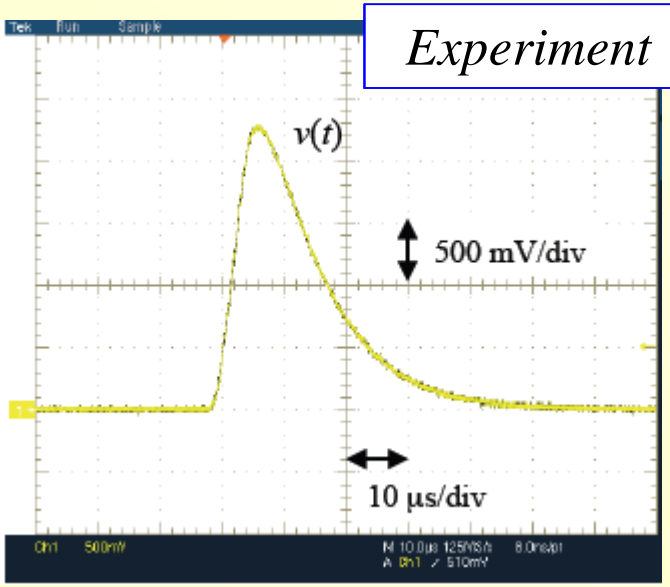


Electrical Model of the Wiegand Source

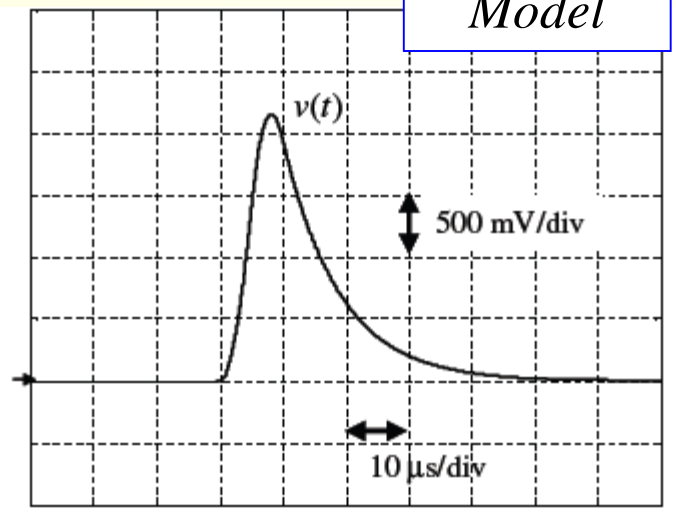
- Simplified model: Thévenin source with resistive-inductive impedance excited by a triangular voltage pulse
- Model fitted from experimental characterization of a commercial sensor
- Results for R_{load} = 1 kΩ:



Experiment

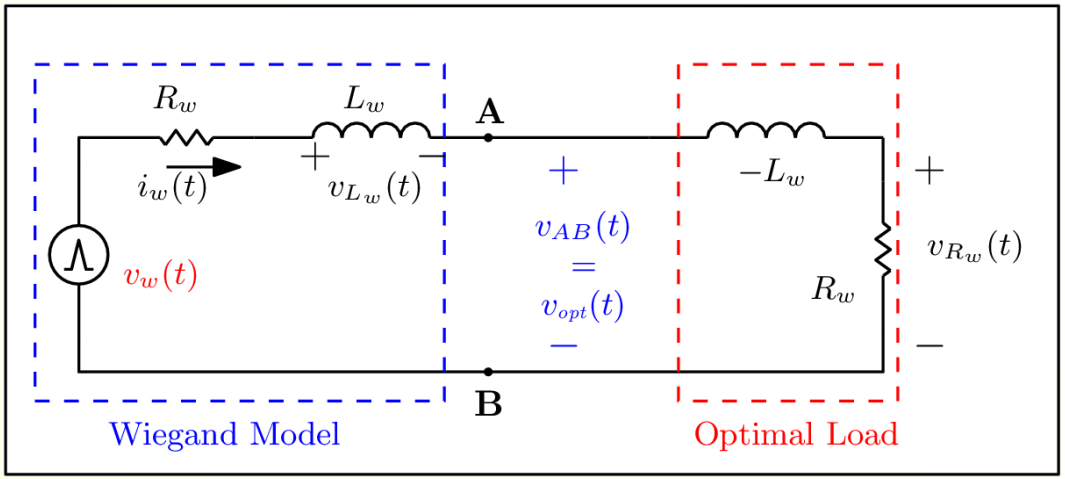


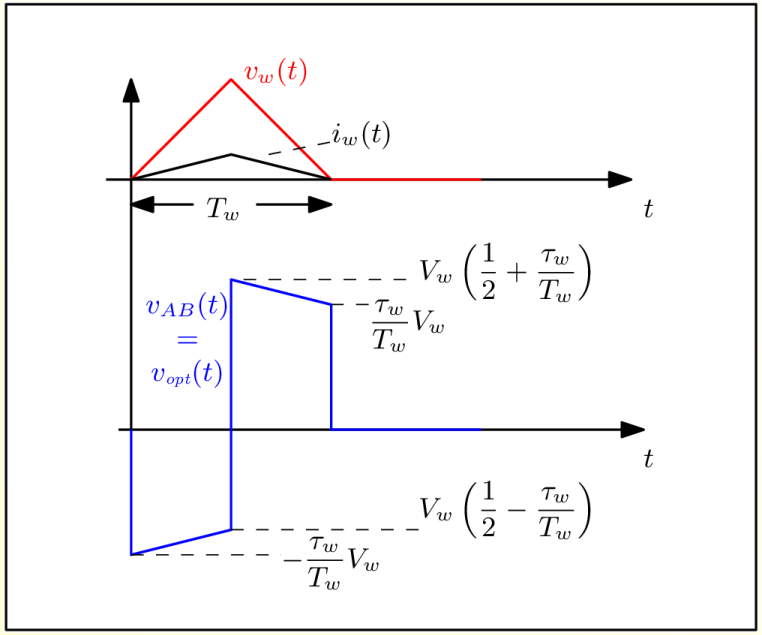
Model



Energy Extraction from the Wiegand Source

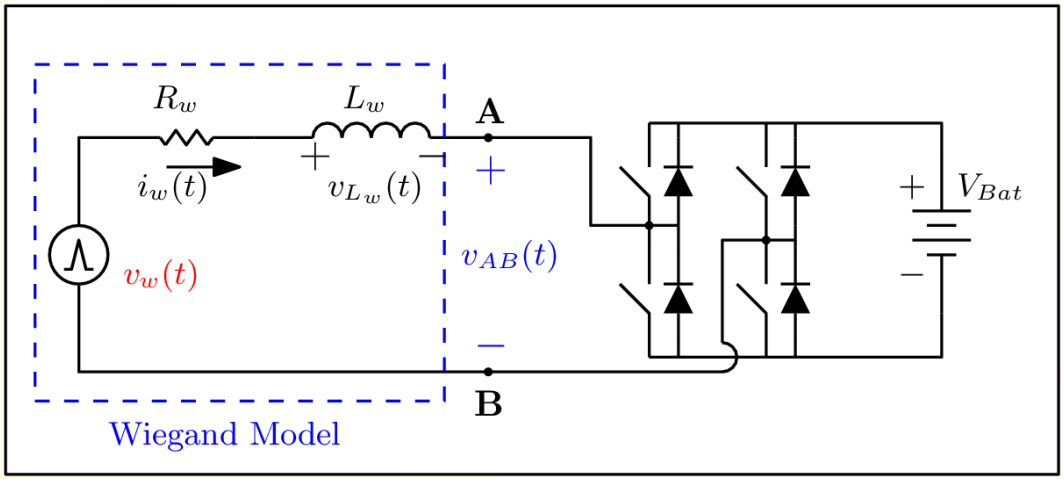
- Optimal load: negative inductance $-L_w$ in series with R_w:
  - Builds up magnetic energy during first half of the pulse
  - Delivers energy to the load during second half of the pulse
- Challenges:
  - Complex optimal waveform $v_{opt}(t)$
  - Optimal voltage level $\approx V_w \tau_w / T_w$ is usually large and unavailable on board
- ➔ **Implement a circuit solution which *approximates* the optimal waveforms using the available battery voltage**

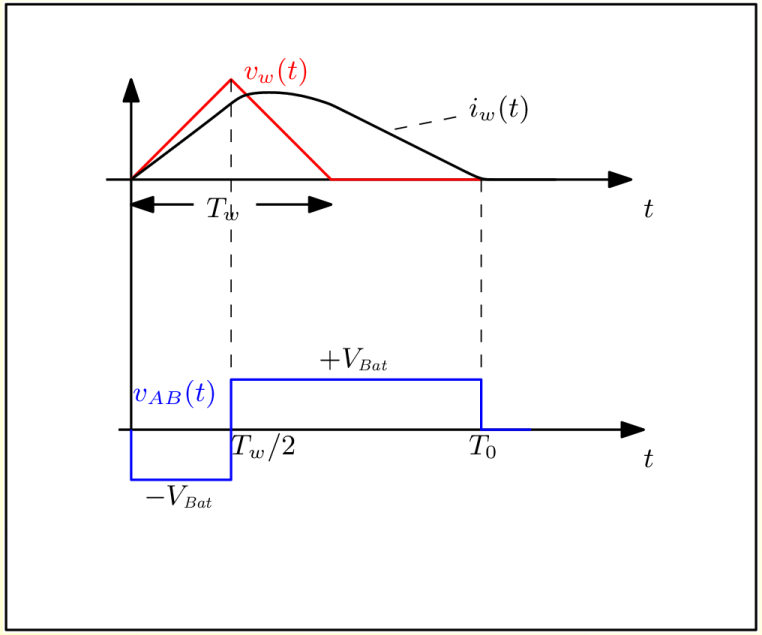




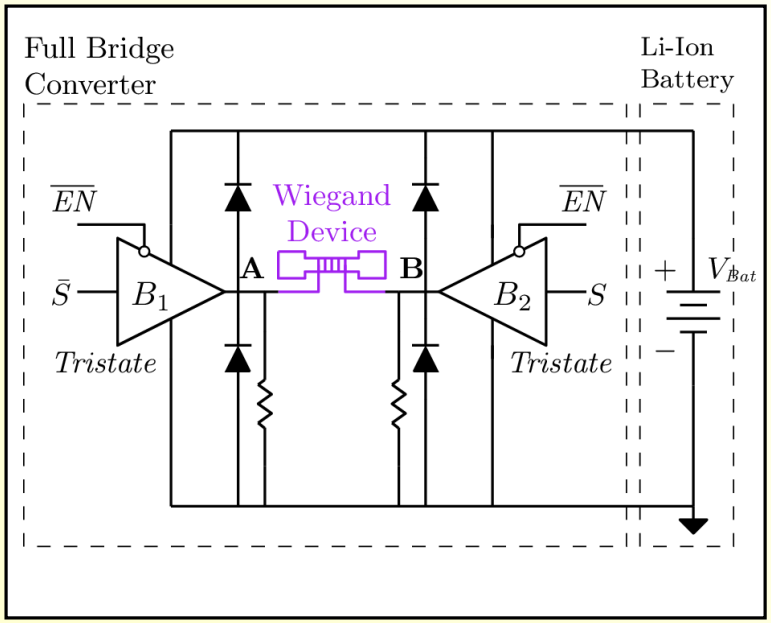
Energy Extraction from the Wiegand Source

- Implemented solution:
  - Use available battery voltage V_{bat} to generate a *rectangular* waveform
  - Apply $\pm V_{bat}$ to the Wiegand source using a *full-bridge topology*
  - Exploit bridge free-wheeling diodes during second half of the pulse
  - Self-trigger the harvesting circuit to the Wiegand pulse

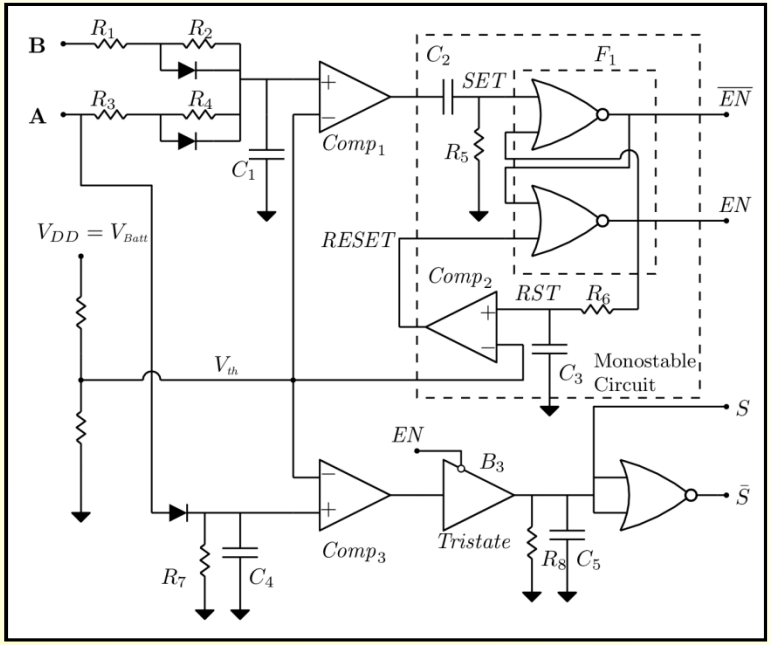




Proposed Wiegand Energy Harvester



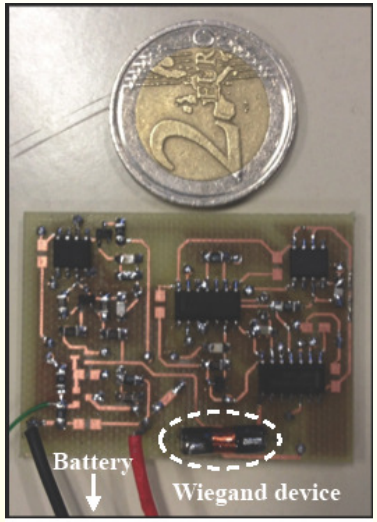
- Full-bridge power harvesting circuit
  - Interfaces Wiegand sensor with a Li-Ion battery via a full-bridge circuit consisting of tristate logic buffers



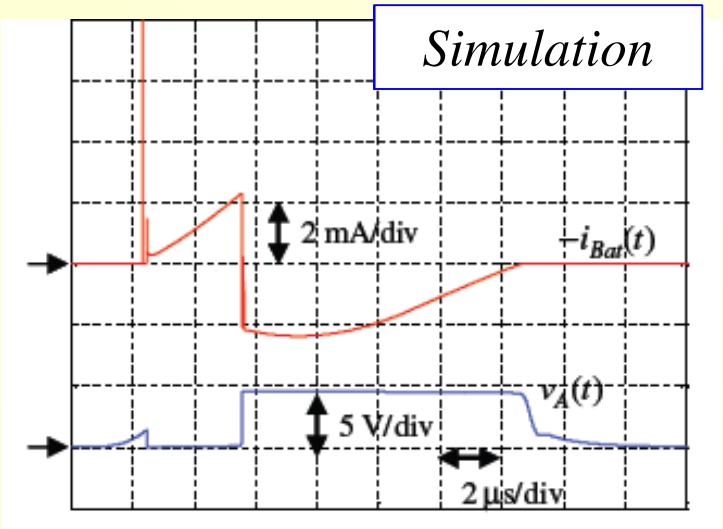
- Self-triggered control circuitry
  - Triggers full-bridge tristate buffers at onset of the Wiegand pulse

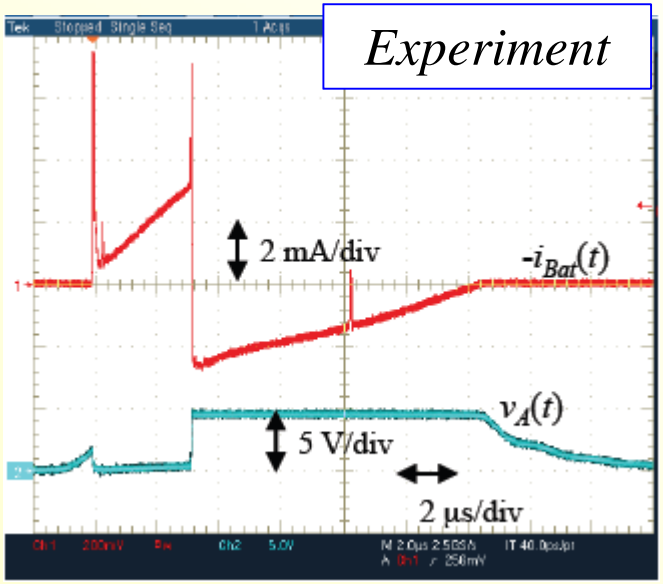
Simulation and Experimental Results

- Wiegand harvesting prototype



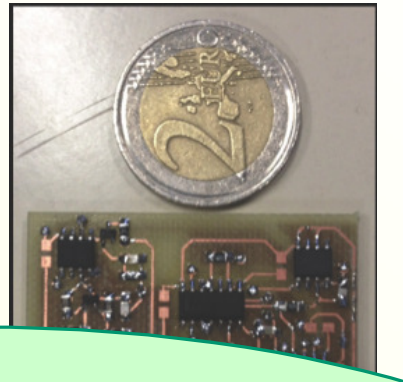
- 24 to 29 nJ/pulse extracted energy
- Simulated vs. experimental performance of the scavenging circuit:





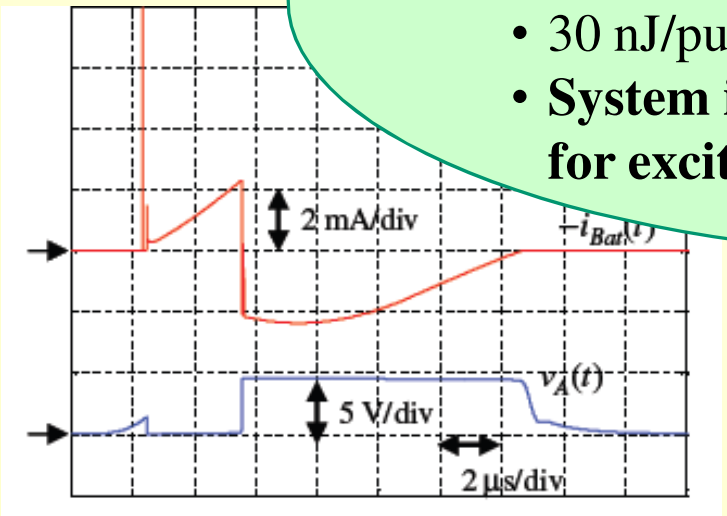
Simulation and Experimental Results

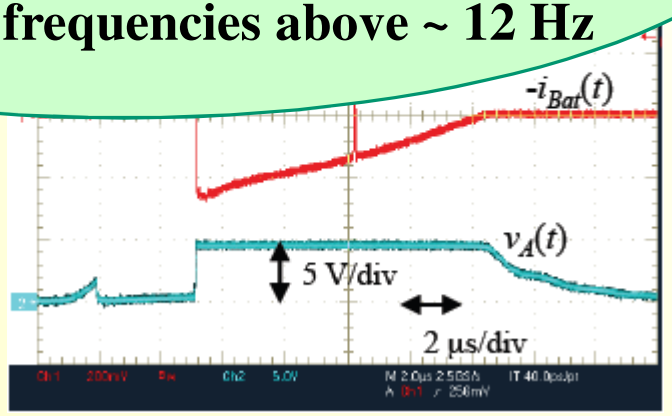
- Wiegand harvesting prototype



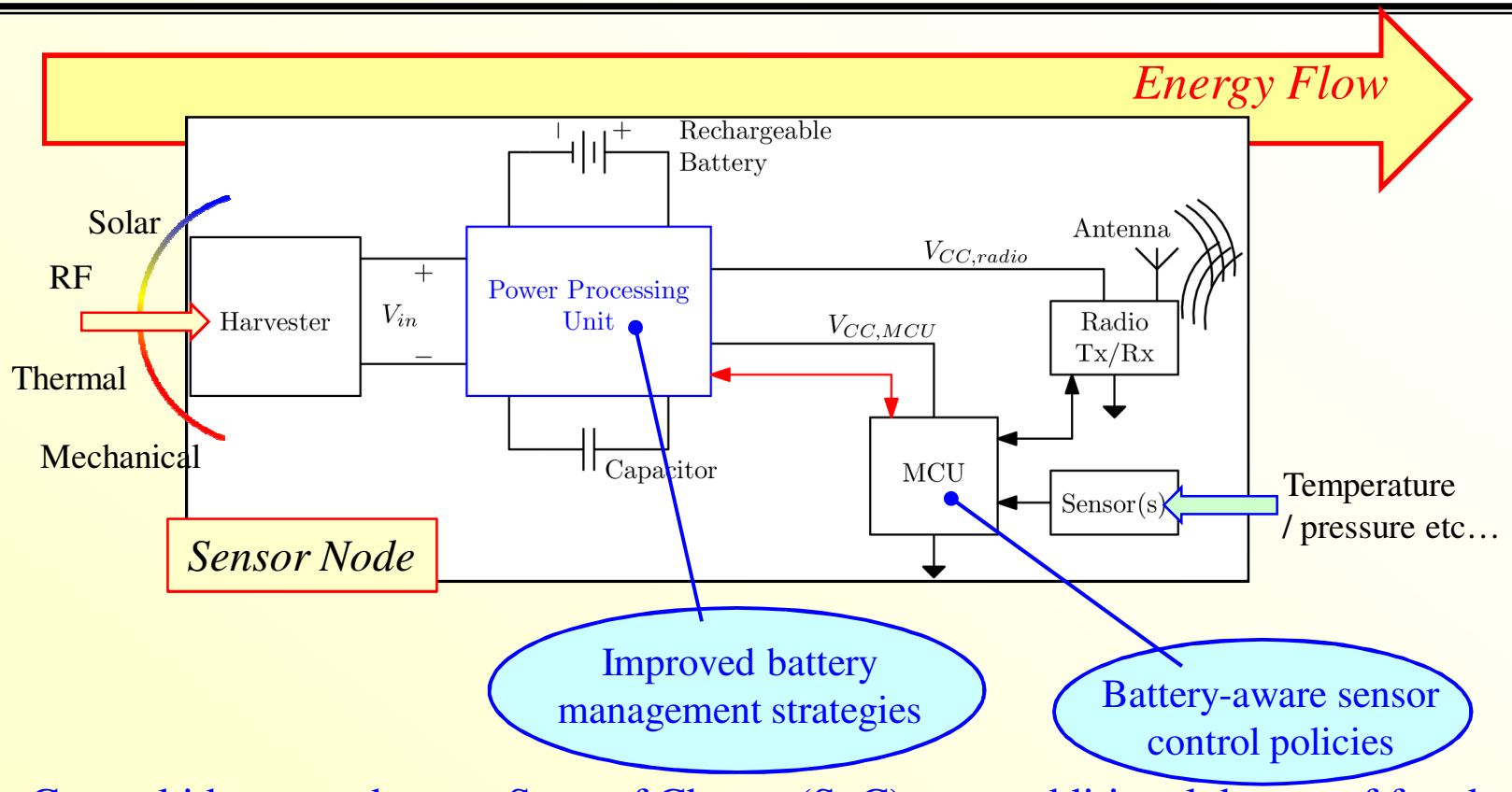
- 24 to 29 nJ/pulse extracted energy
- Simulated vs. experimental scavenging circuit:

Example:
- 100 nA sensor sleep current
- 3.7 V battery voltage
- 30 nJ/pulse harvested energy
- **System is energetically autonomous for excitation frequencies above ~ 12 Hz**





Advanced Battery Management



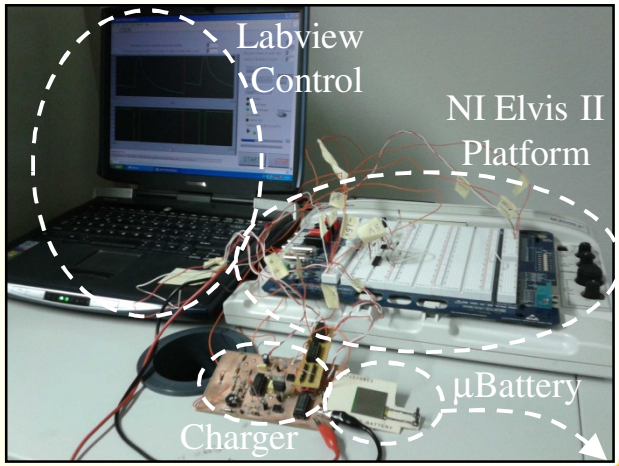
- General idea: treat battery State of Charge (SoC) as an additional degree of freedom
  - Improved battery management (depth of discharge *vs* degradation)
  - Quality of service *vs* energy autonomy tradeoffs
  - Exploit SoC information at network level

State of Charge-Aware Sensor Node Development

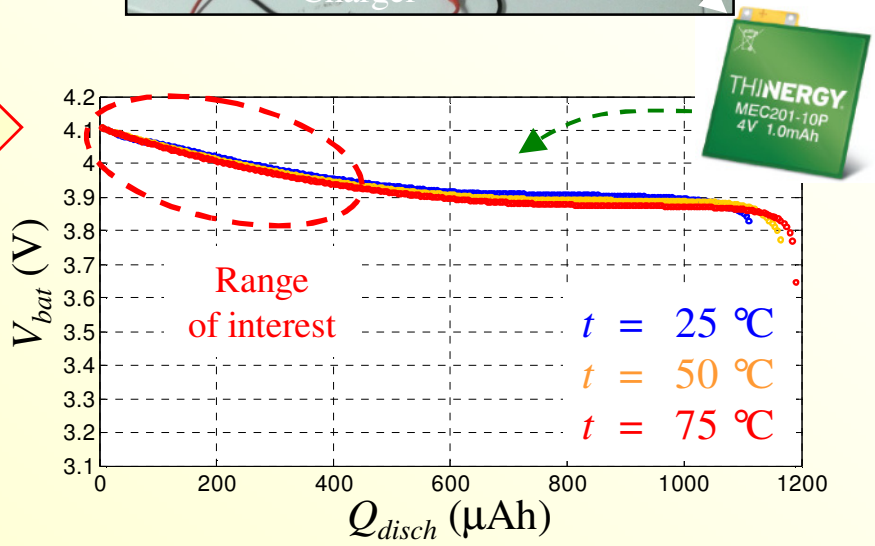
- Goal is to exploit the battery State of Charge (SoC) information for improved sensor management:
  - Modulate sensor Tx rate as a function of the battery SoC
  - Rapidly recharge the battery as soon as power is available
  - Avoid harmful, deep battery discharges
- Ongoing activity:
  Development of a harvesting-based sensor node test bed capable of
  - Sensing / transmitting a measured quantity (e.g. temperature)
  - Estimating own battery SoC
  - Implementing a SoC-aware management policy
- Related Tasks
  - Microbattery characterization
  - Power consumption characterization / breakdown of a commercial energy harvesting development platform

State of Charge-Aware Sensor Node Development

- Microbattery Characterization
  - Developed a custom charging/discharging setup for µBattery testing



  - Conducted *C*/10 discharge tests at different temperatures



  - Goal is to correlate open-circuit voltage with SoC at low DoD's
  - Currently evaluating the need for temperature compensation

Conclusions

- WSAN Interdisciplinary Research Team @ DEI
- WSAN Initiative in the Energy Harvesting field: University-funded Research Project addressing
  - Sensor power management
    - Innovative energy harvesting solutions
    - Improved battery management for prolonged life time
    - Energy-aware sensor control
  - Smart network energy management
    - Network-level usage of the energy information
    - Energy-aware routing protocols
- Thank You and Enjoy the Next Talks!