Energy Scheduling for Task Execution on Intermittently-Powered Devices

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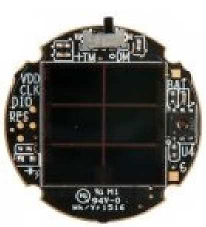
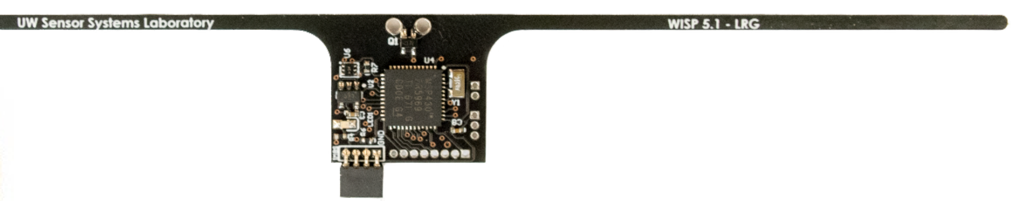
Intermittently Powered Devices

- **Definition**: Devices that do not use battery and are powered by intermittent power sources such as sunlight, heat, vibration, and radio signals.
- **Applications**: Smart home, agriculture, health monitoring, …
- **Advantages**:
  - Few maintenance is required
  - They can last for decades
  - They can be deployed in extreme environments
- **Examples** : Beacon, WISP, Flicker, ...

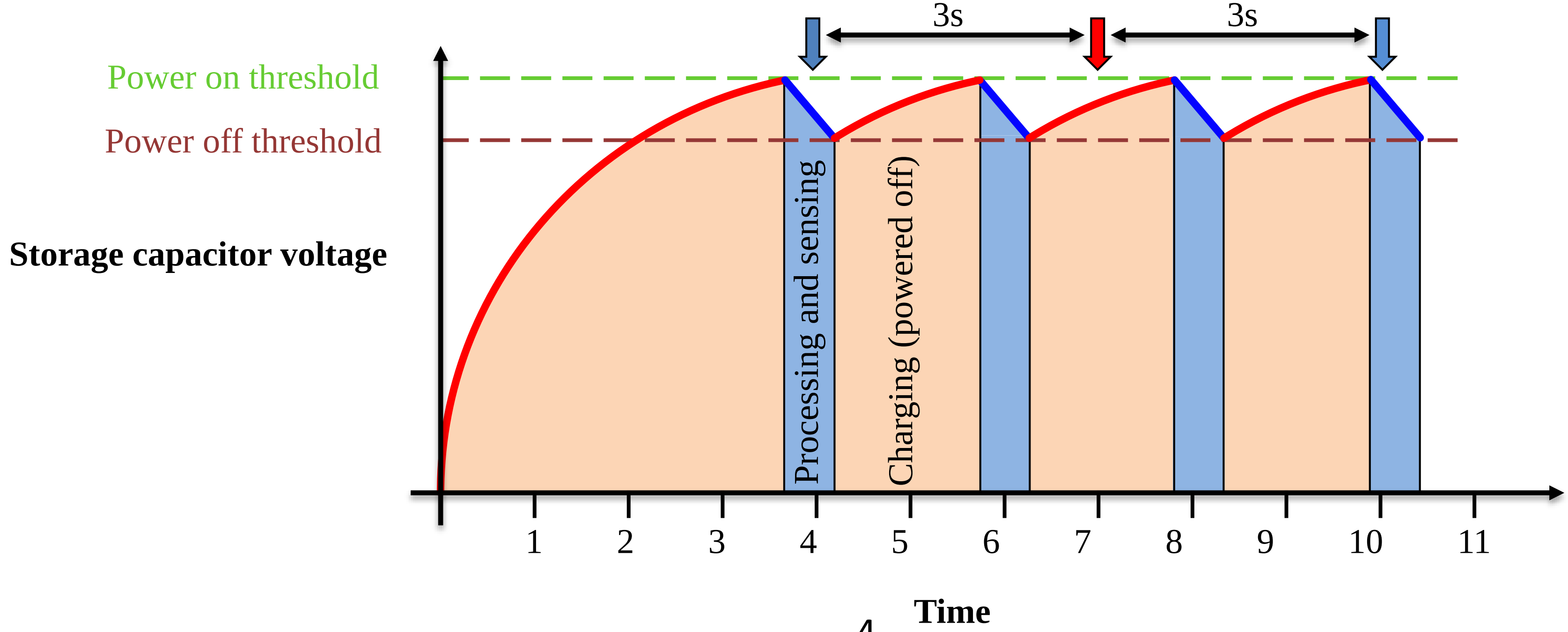
Previous Work

- Forward progress guarantee (checkpointing)[1,2]
- Programming environment to divide tasks into segments to preserve data consistency[3]
- Different energy storage banks for different types of task [4]
- Event-driven Kernel for intermittently powered devices[5]

[1] A. Colin, E. Ruppel, and B. Lucia. A Reconfigurable Energy Storage Architecture for Energy-harvesting Devices. In ACM SIGPLAN Notices, volume 53, 2018.
[2] B. Ransford, J. Sorber, and K. Fu. Mementos: System support for long-running computation on rfid-scale devices. In ASPLOS, 2011.
[3] J. Hester, K. Storer, and J. Sorber. Timely Execution on Intermittently Powered Batteryless Sensors. In SenSys, 2018.
[4] A. Colin, E. Ruppel, and B. Lucia. A Reconfigurable Energy Storage Architecture for Energy-harvesting Devices. In ACM SIGPLAN Notices, volume 53, 2018.
[5] K. S. Yildirim, A. Y. Majid, D. Patoukas, K. Schaper, P. Pawelczak, and J. Hester. InK: Reactive Kernel for Tiny Batteryless Sensors. In SenSys, 2018.

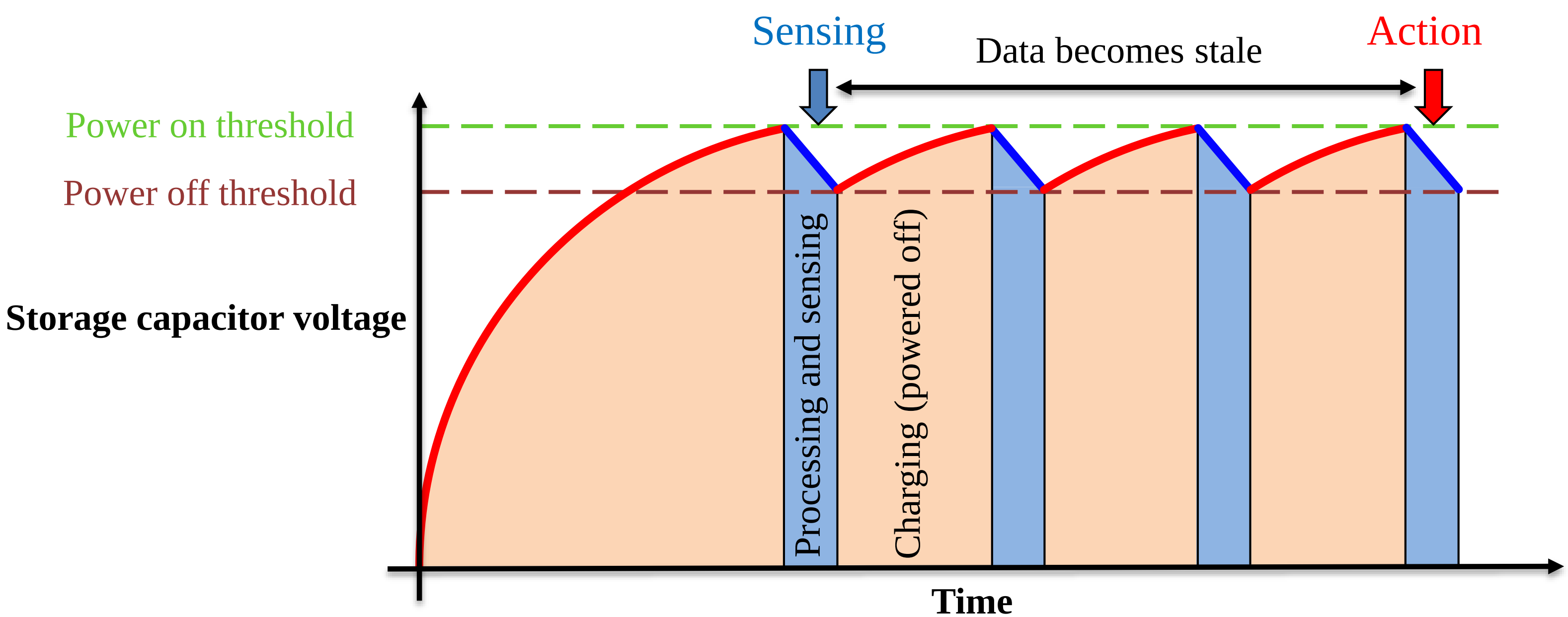
Challenges

- Periodic sensing and real-time task execution
  - Device goes off in every power cycle
    - Discharging is much faster
    - Energy buffer is extremely small (e.g., capacitors with 47 uF@1.8V)
  - No notion of time



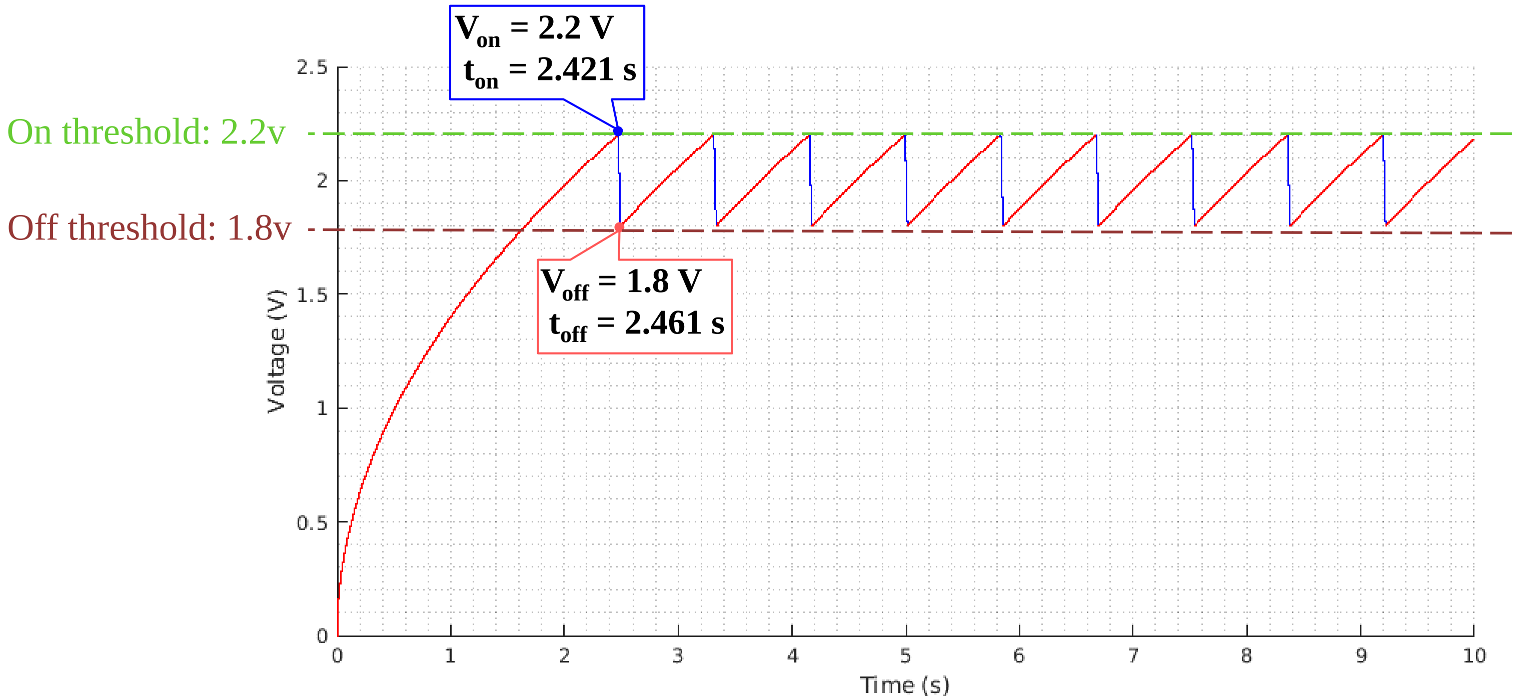
Challenges

- Data freshness and timely execution
  - Importance
    - On time detection (sensing) and in-time reaction
  - Requirement
    - Periodic sampling and time keeping
  - Example
    - Blood sugar monitoring and automatic insulin release for a diabetic



Challenges

- Long atomic (indivisible) execution
  - Sensor reading
    - Example: BME680 gas sensor needs more than 100ms to read sensor value



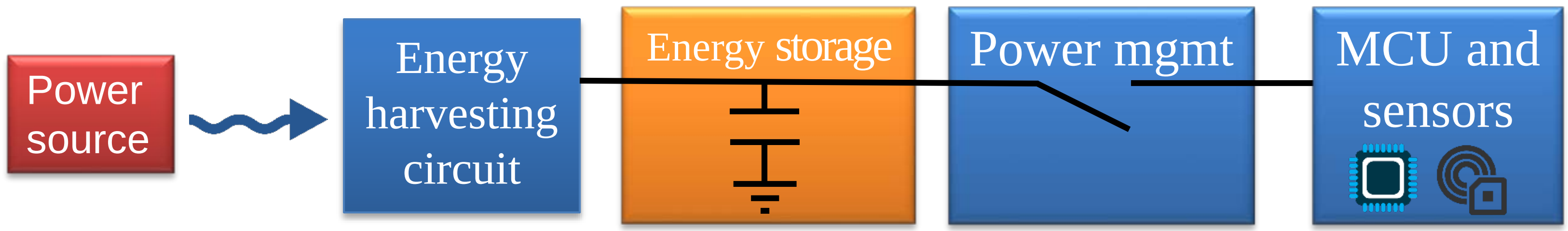
$t_{off} - t_{on} = 40ms$

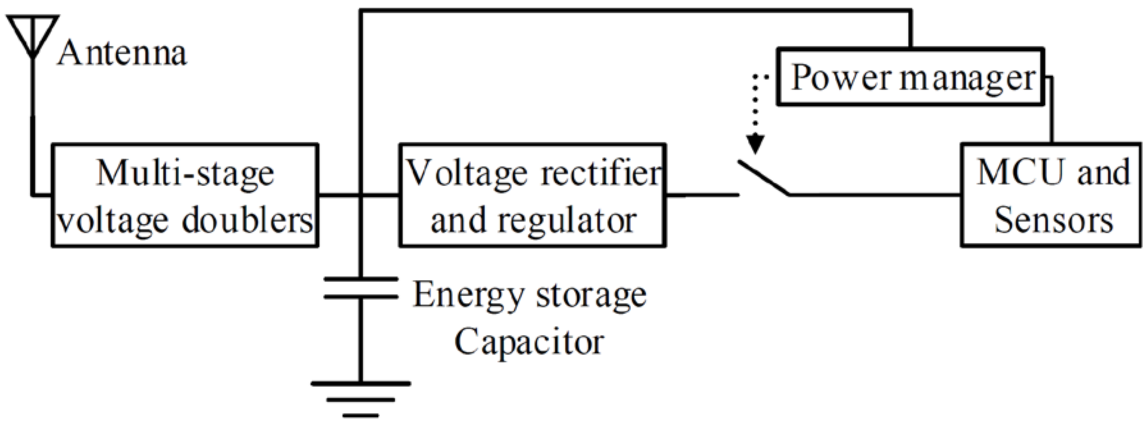
Proposed Method

- Energy scheduling model
  - Keep track of time
  - Enable periodic task execution
  - Enable atomic indivisible execution
- Real-time task scheduling analysis
  - Single task
  - Multiple task

System Model

- Hardware characteristics





System Model

- RFID tag
  - G_s: Transmitter gain
  - G_r: Receiver gain
  - L_p: Polarization loss
  - η : Rectifier efficiency factor
  - λ : Wavelength of the RF signal
  - β : Parameter to adjust Friis' free space equation for short distance

$$P_r = \frac{G_s G_r \eta}{L_p} \left(\frac{\lambda}{4\pi(d+\beta)} \right)^2 P_t \quad [6] \quad \longrightarrow \quad P_r = \alpha \left(\frac{1}{d+\beta} \right)^2 P_t$$

- Fixed distance from reader:
  - C_s: Storage capacitor
  - R_p Parallel equivalent resistance of the circuit

$$\frac{P}{V} = C_s \frac{dV}{dt} + \frac{V}{R_p} \quad \longrightarrow \quad t_{charging} = \frac{C_s R_p}{2} Ln \left(\frac{PR_p - V_0^2}{PR_p - V^2} \right)$$

[6] S. He et al. Energy provisioning in wireless rechargeable sensor networks. IEEE Transactions on Mobile Computing, 12(10):1931–1942, Oct 2013.

System Model

- Charging rate
  - V_{min_th}: Min voltage required to turn on the device
  - V_{max}: Max voltage of the capacitor
  - R_P: Parallel equivalent resistance of the circuit
  - C_s: Storage capacitor

$$m_c = \frac{V_{min\_th} - V_{max}}{\frac{C_s R_p}{2} Ln\left(\frac{PR_p - V_{min\_th}^2}{PR_p - V_{max}^2}\right)}$$

- Discharging rates
  - m_D: Decaying
  - m_P: Processing
  - m_W: Waiting

$$m_d = \max\{m_W, m_D\}$$

- Overall charging rate
  - MCU in sleep mode
  - Power source is available periodically
    - T_c: Charging period
    - C_c: Charging time in each period

$$m_a = \frac{m_c \times C_c - m_d \times (T_c - C_c)}{T_c}$$

$$V = m_a \times \Delta t + V_0$$

Energy scheduling scheme

- Goal: Provide system-level support for periodic sensing tasks on intermittently-powered devices

- Approach: Schedule "energy" w.r.t. task execution requirements
  - Find the voltage level that is required for the completion of a single instance of a task (job) without power interruption
    - Higher voltage on capacitor → Supports longer job execution
      → but suffers from longer waiting time (charging)
  - Control device wake-up and task invocation time
    - Enable overcharging the capacitor by enforcing the low power mode (LPM3)
    - Wake up the device at the right time after reaching the computed voltage level and before task deadline

Task Scheduling

- Capacitor voltage for n tasks
  - m_{Pi} : Discharging rate of task i
  - s_i : Indicates if the last job of task i is serviced or not (0 or 1)
  - T_i : Period of task i
  - C_i : Execution time of task i

$$V_{cap}(t) = m_a * t - \sum_{i=1}^{n} \left(\left\lfloor \frac{t}{T_i} \right\rfloor + s_i \right) * C_i * m_{Pi} + V_0$$

- Single task scheduling

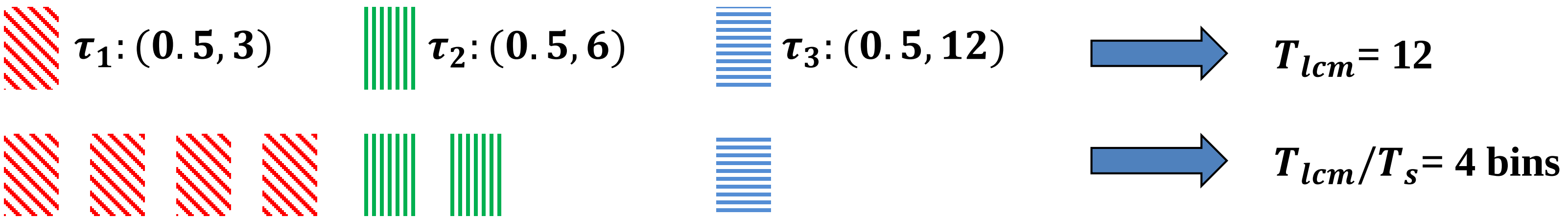
$$m_a > 0 \qquad m_a \times T_1 > m_{P1} \times C1$$

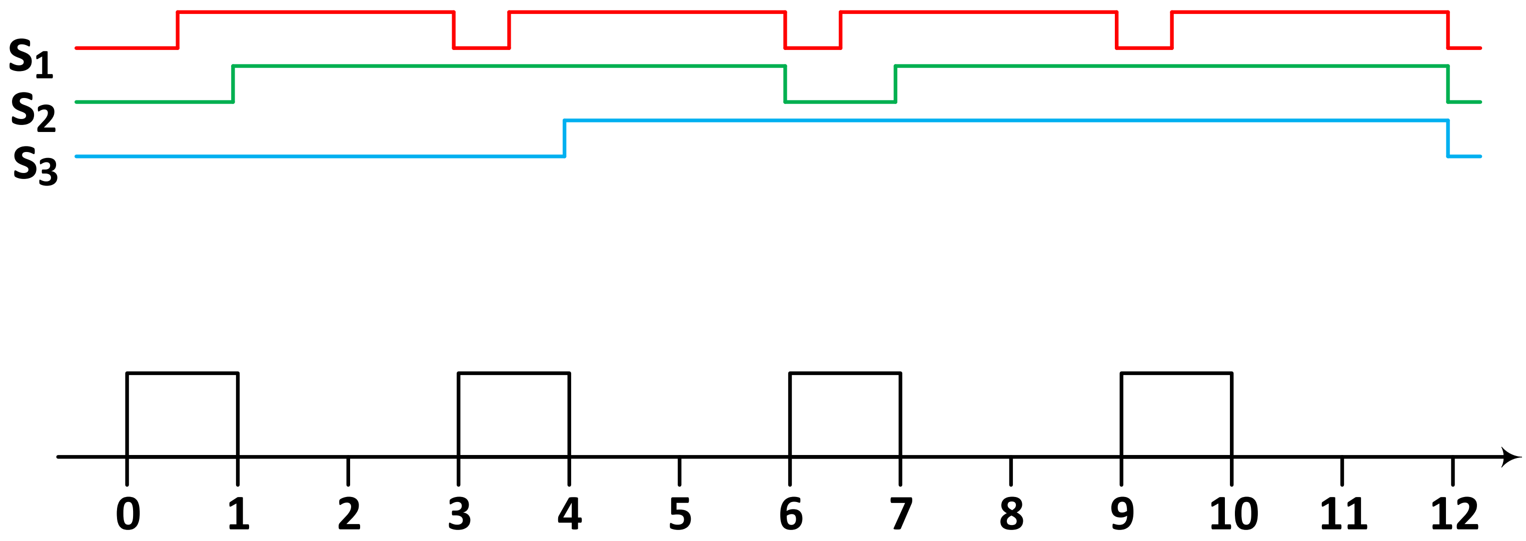
Task Scheduling

- Multi tasks scheduling
  - Periodic server with period T_s
  - Non-preemptive
  - Modeled as bin-packing problem
    - Items: jobs of each task
    - Bins: amount of budget per period
    - Number of bins: T_{lcm}/T_s
    - No more than one job from the same task in each bin
  - Finding efficient server parameters is an NP-hard problem

Task Scheduling

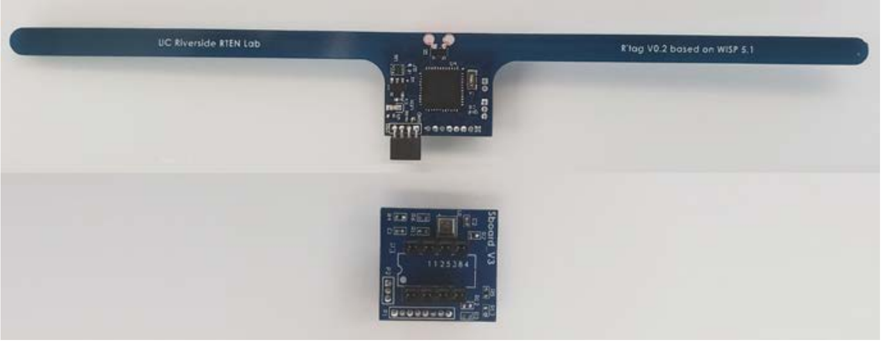
- Server with period of 3s and budget of 1

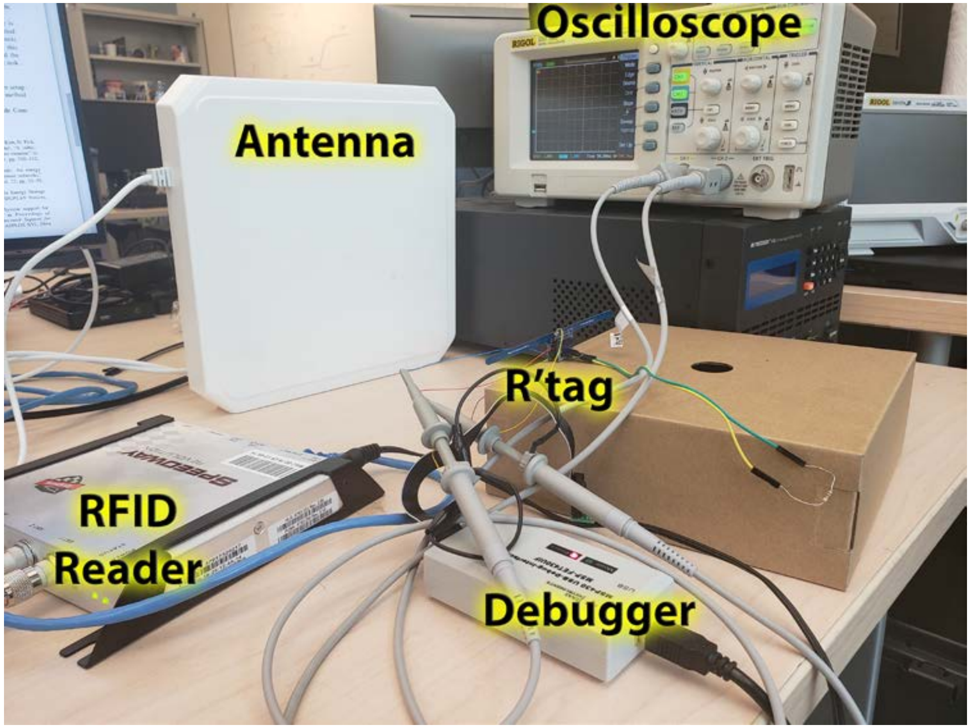




Implementation

- Impinj R420 Reader
- R’tag
  - Based on WISP [7]
  - MSP430 MCU
  - Sensor board
  - Resistive sensor
- RFMAX S9028PCL Antenna
  - Directional with 8dbi gain

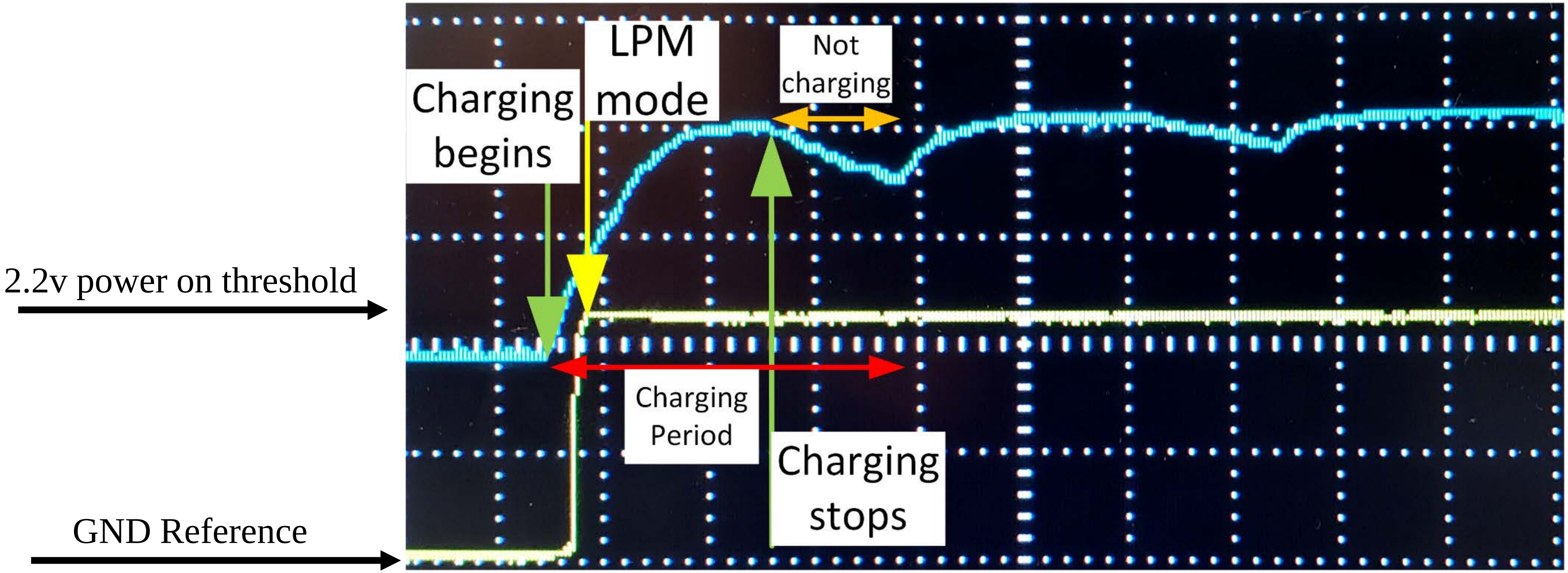




[7] A. P. Sample et al. Design of an RFID-based battery-free programmable sensing platform. IEEE Trans. on Inst. and Measurement, 57(11):2608–2615, 2008.

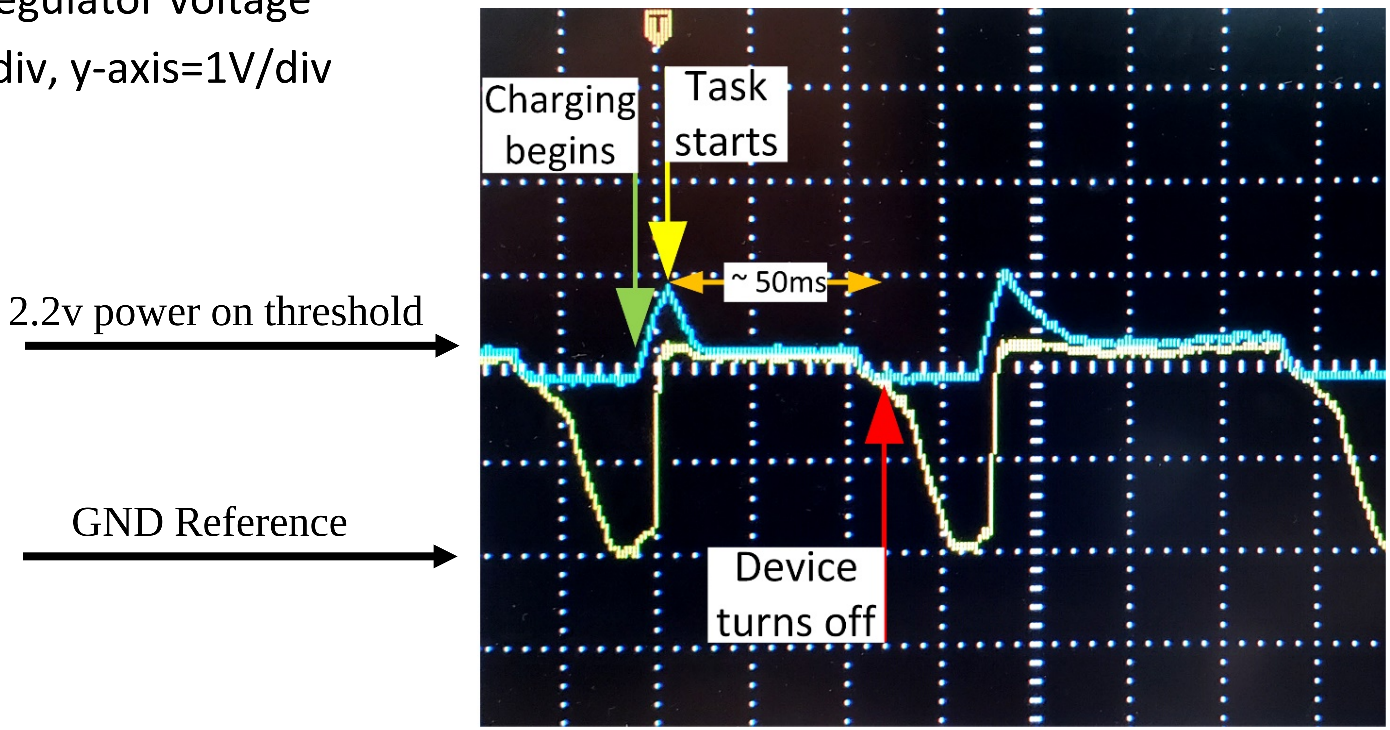
Evaluation

- Charging and discharging times
  - Blue line: Storage capacitor voltage
  - Yellow line: Regulator voltage
  - x-axis=20ms/div, y-axis=1V/div



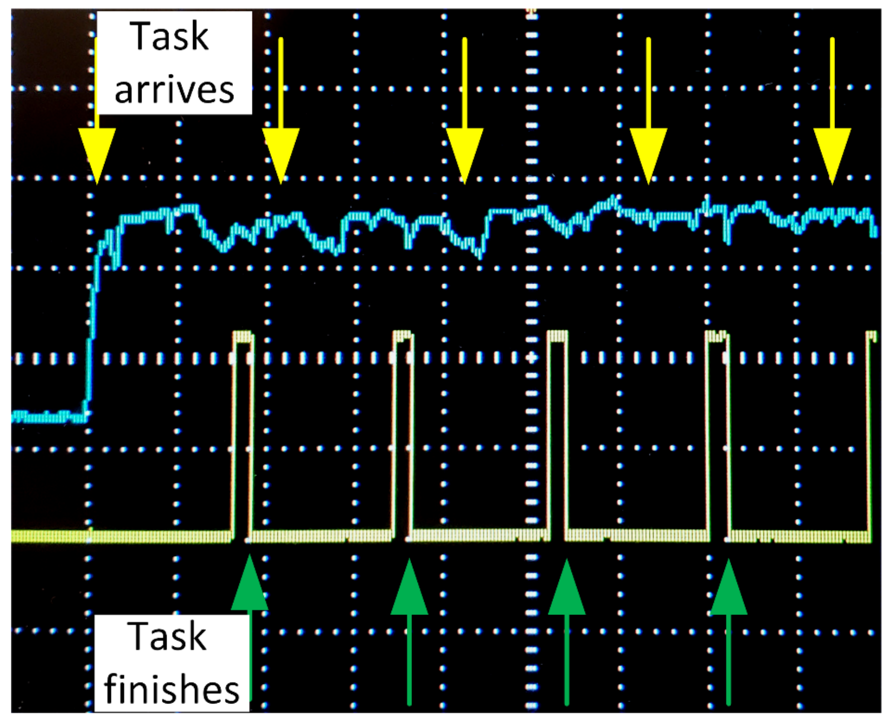
Evaluation

- Experimental results
  - Execution time: 120ms
  - Period 1s
  - Blue line: Storage capacitor voltage
  - Yellow line: Regulator voltage
  - x-axis=20ms/div, y-axis=1V/div



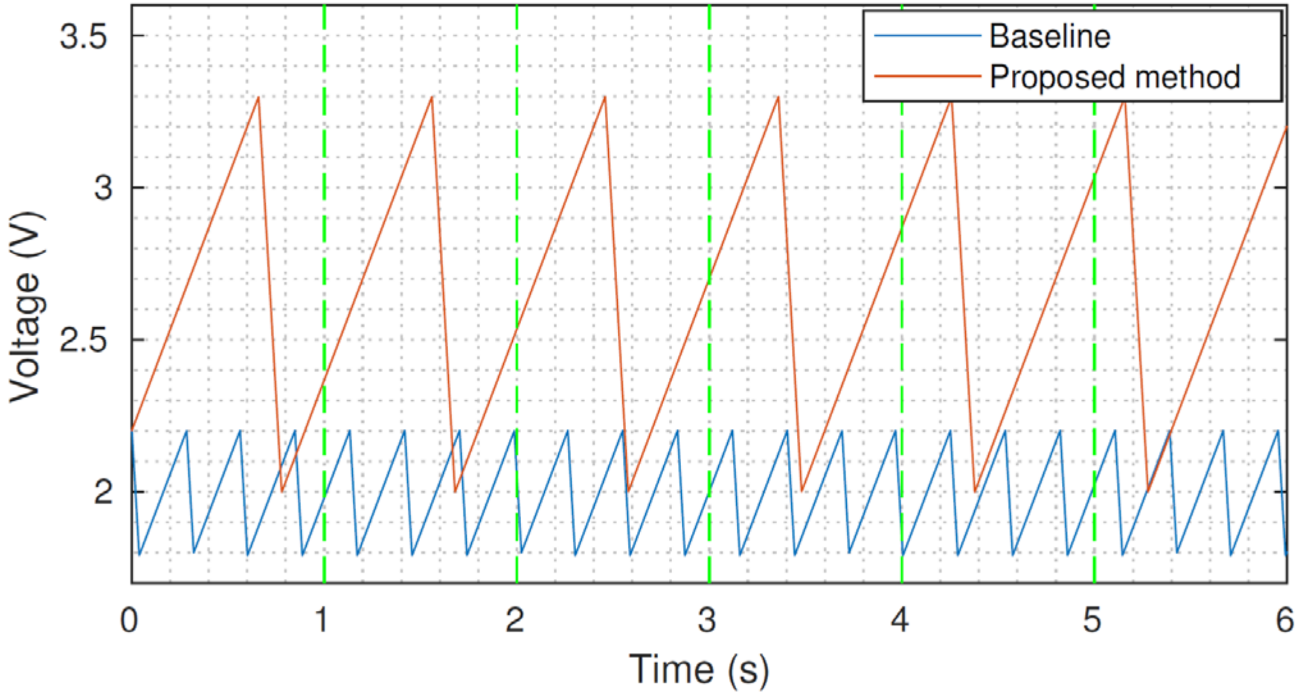
Evaluation

- Experimental results
  - Execution time: 120ms
  - Period 1s
  - Blue line: Storage capacitor voltage
  - Yellow line: I/O indicating task is running
  - Yellow arrows: Task arrivals
  - Green arrows: Task finish time
  - x-axis= 500ms/div, y-axis=1V/div



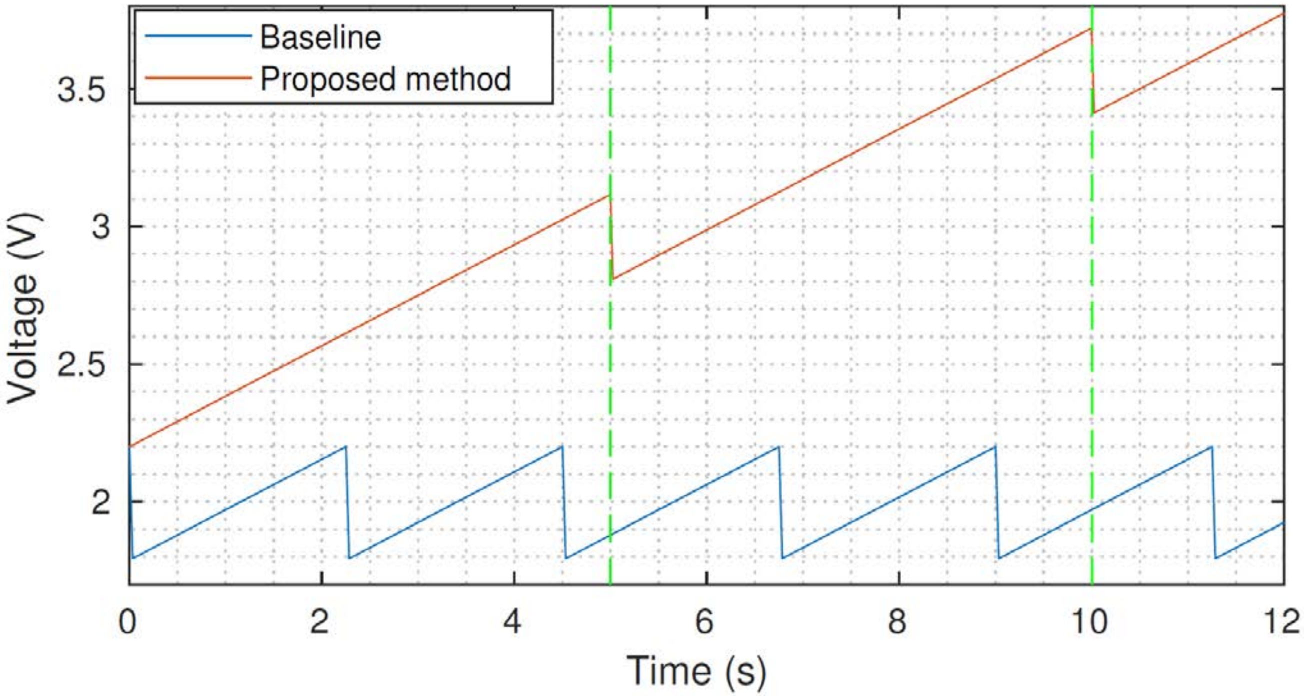
Evaluation

- Simulation
  - Task execution time: 120ms
  - Task period: 1s



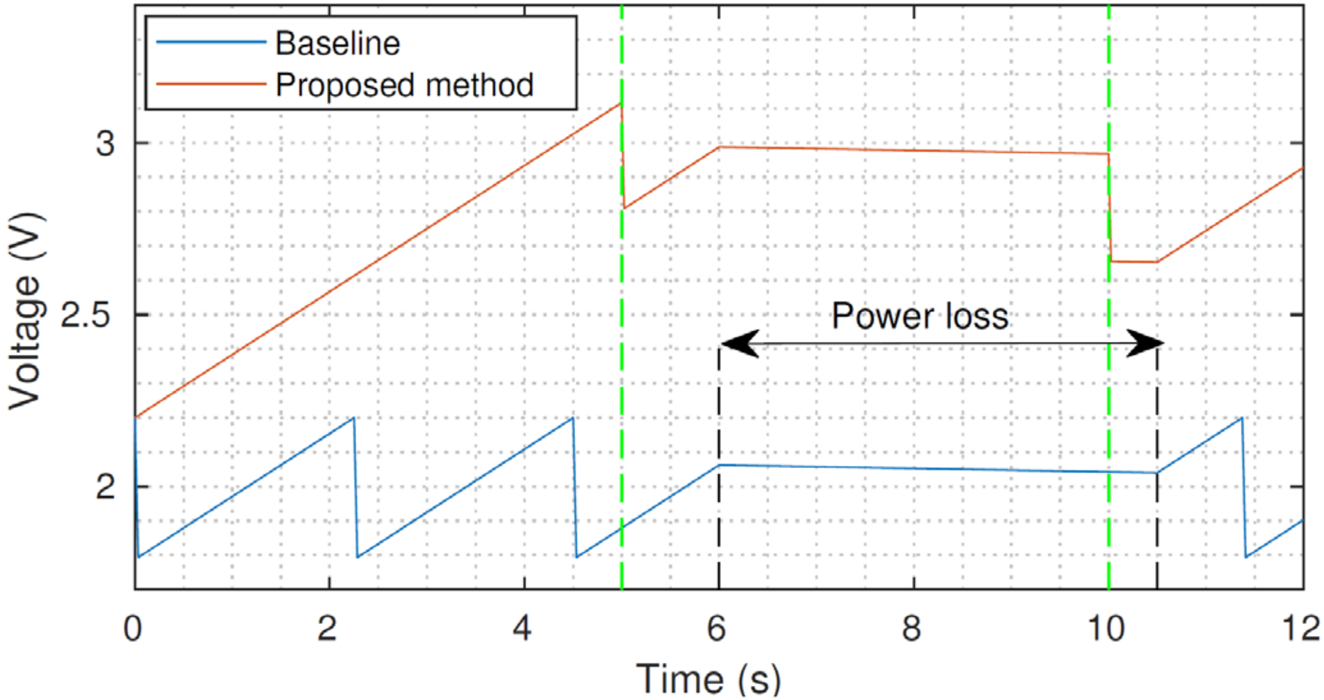
Simulation

- Simulation
  - Task execution time: 25ms
  - Task period: 5s



Simulation

- Simulation
  - Task execution time: 25ms
  - Task period: 5s
  - In presence of power loss



Conclusion

- **Energy scheduling scheme**
  - Keeps track of time
  - Enables periodic sensing
  - Considers real-time task scheduling
- **Implementation**
  - Effective in real sensing applications
  - schedule the periodic task
- **Simulation**
  - Outperforms the baseline approach
  - Effectiveness if unexpected power loss
- **Further improvements**
  - Algorithm to find the efficient server parameters in multi-task scenario
  - Applying the method to existing platforms (e.g. *InK*)
  - Additional hardware to address tasks with longer executions (like *Capybara*)

Thank You