Modeling Energy and Performance in Energy Harvesting IoT Systems

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1 Introduction

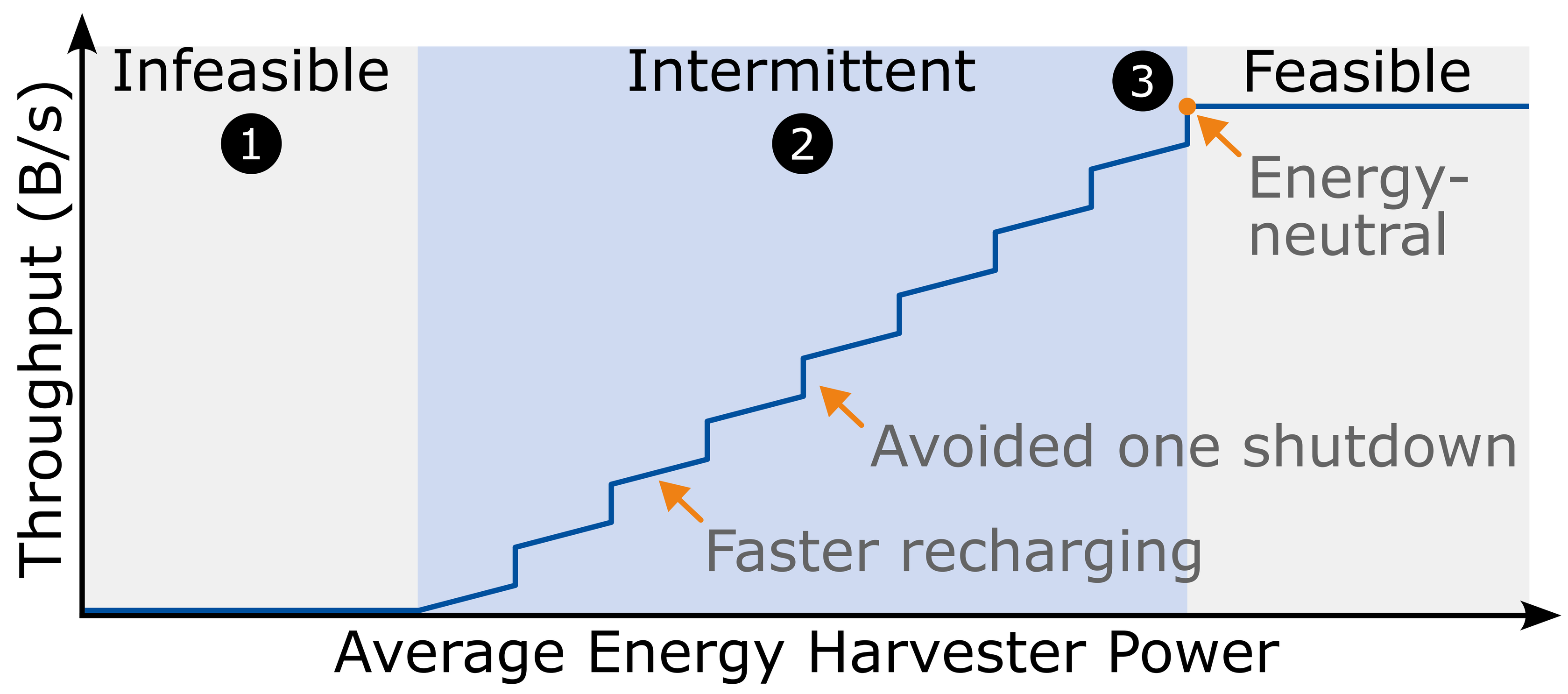
- The rapid proliferation of IoT systems underscores the urgency for efficient energy management strategies due to the impracticality of widespread battery replacement.
- Energy harvesting emerges as a vital alternative for many IoT systems, necessitating careful optimization to balance energy consumption of the SoC with the power supplied by harvesting subsystems.
- These challenges create a complex problem for IoT system developers:

1. Selecting and sizing components (energy harvester, storage, processor, radio subsystem) is crucial for meeting throughput requirements while minimizing costs and size.
2. Evaluating IoT devices becomes challenging due to growing complexity and proprietary communication protocols. Additionally, assessing IoT systems, especially those utilizing outdoor solar harvesters with high variability, takes significant time. This impracticality for real-time applications leads to prolonged evaluation periods.
3. Optimizing runtime behavior is essential for maximizing throughput despite varying power output of energy harvesters.

- In this work, we addressed these challenges respectively by applying analytical modeling along three distinct research directions: (i) Periodic Energy Harvesting Systems (PES), (ii) The Energy Subsystem Simulator (ESS), and (iii) Energy-Aware Connection Management (ECM).

2 PES: Periodic energy harvesting systems

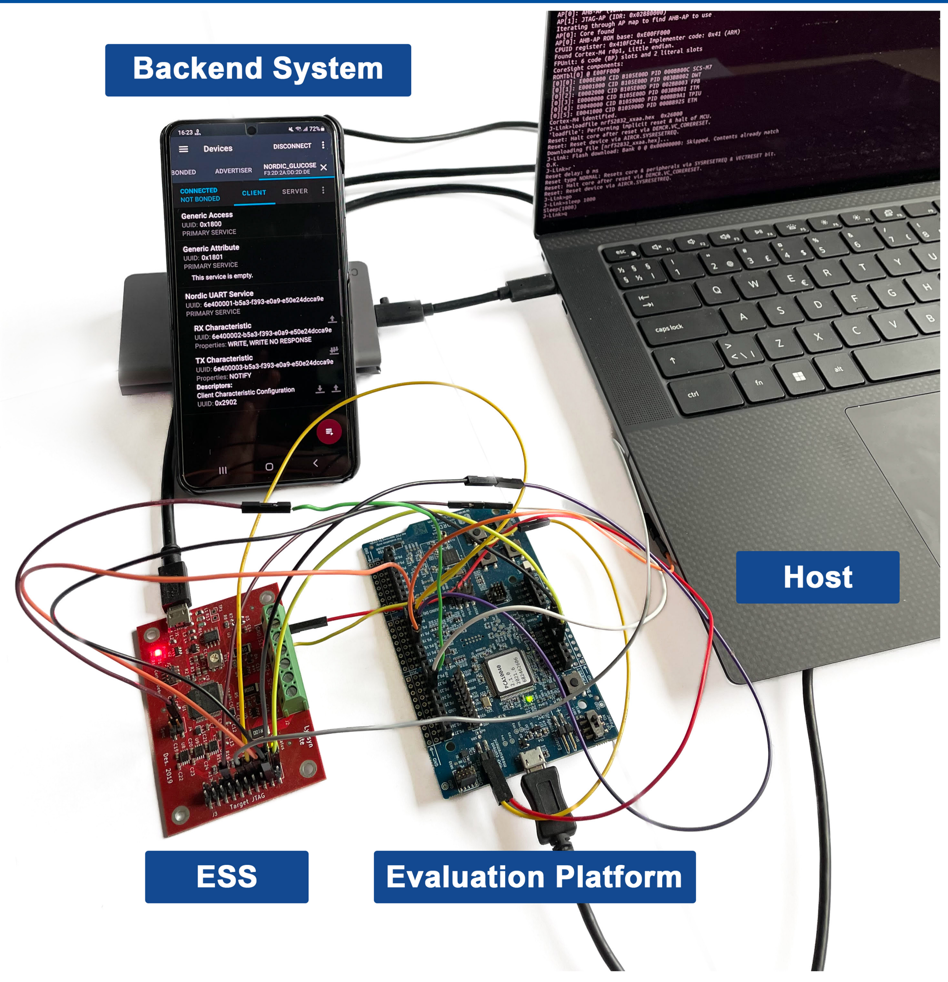
- We introduce the analytical Periodic Energy Harvesting Systems (PES) model, which enables IoT developers to optimize energy-harvesting IoT systems by evaluating energy-throughput trade-offs in early design phases.



- PES also enables the creation of energy rooflines which illustrate how application throughput responds to changes in the average power output of the energy harvesting subsystem. The energy roofline comprises three regions: (i) infeasible, (ii) intermittent, and (iii) feasible.
- PES achieves high accuracy, with an average prediction error of only 3.6% across diverse IoT applications.

3 ESS: The energy subsystem simulator

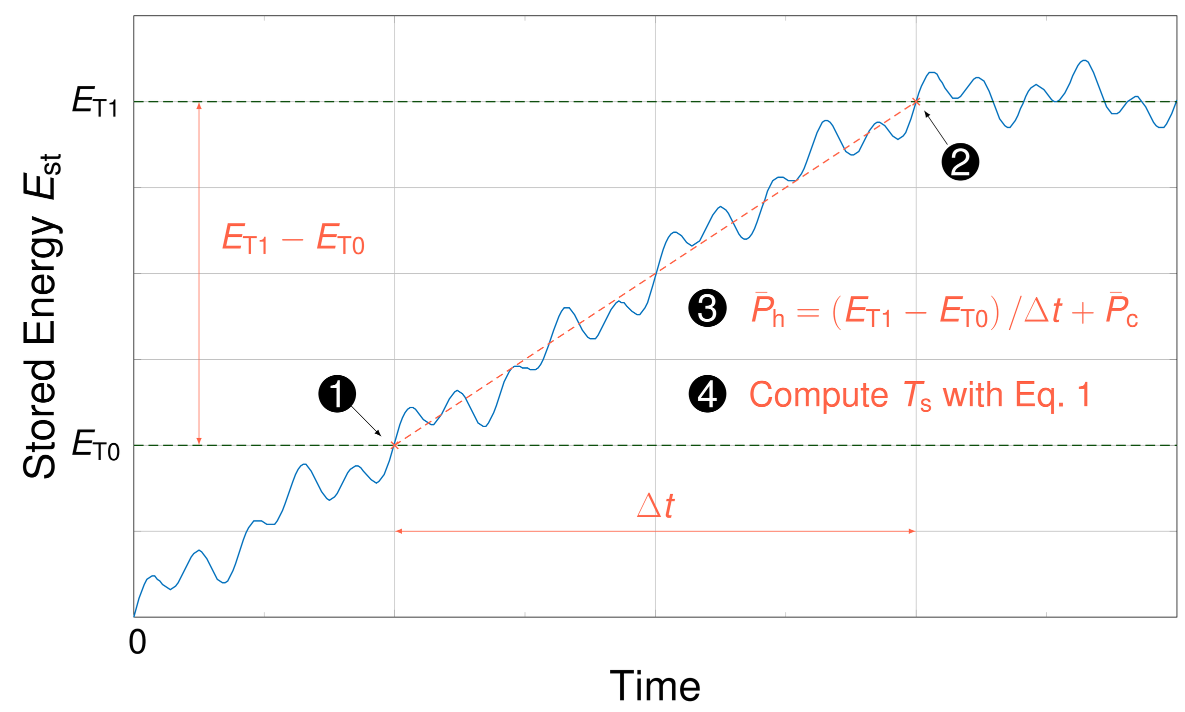
- We introduce the Energy Harvesting Subsystem Simulator (ESS). ESS utilizes recorded energy traces from the host and measures the application SoC's power consumption.
- Additionally, we propose Compress Inactive (CIN) to reduce evaluation time for periodic IoT applications.
- ESS, coupled with CIN, reduces IoT system evaluation time by up to 516.0× with an average prediction error of only 0.2% (0.8%).



4 ECM: Energy-aware connection management

- ECM achieves near-energy-neutral operation by first predicting the average power output of the energy harvester $\bar{P}_h$ and then predicting a sampling period T_s that balances energy supply and demand.

$$T_s = \frac{E_c^*}{\bar{P}_h - \bar{P}_c^*}.$$



- ECM operates near the energy-neutrality point, thereby reducing the need for management tasks and ultimately improving throughput.
- ECM improves throughput by up to 9.5× and 3.0× compared to the on-demand connect and maintain connection policies, respectively.

5 Summary

- We proposed PES, which uses analytical modeling to enable developers to select favorable design points early in design process.
- We presented ESS, which uses analytical modeling to enable evaluation of industry-grade IoT systems and speeds up evaluation.
- We introduced ECM which uses analytical modeling to optimize the connection policy and sampling period and thereby achieve near-energy-neutral operation.

6 Further reading

- Fatemeh Ghasemi and Magnus Jahre.
  Modeling periodic energy-harvesting computing systems.
  IEEE Computer Architecture Letters, 20(2):142–145, 2021.
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  ECM: Improving IoT throughput with energy-aware connection management.
  In *Design, Automation and Test in Europe Conference (DATE)*, 2024.