A Little Certainty is All We Need: Discovery and Synchronization Acceleration in Battery-Free IoT

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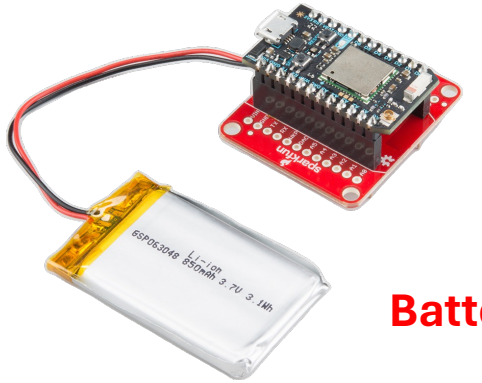
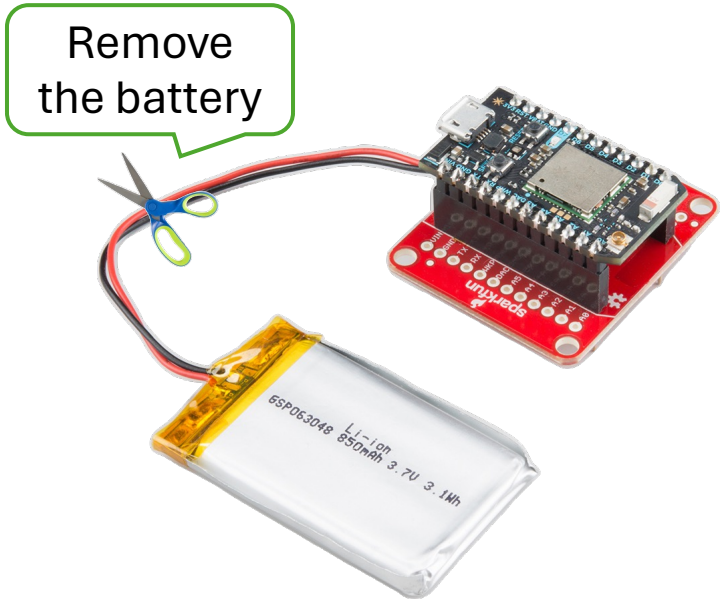
Sustainability issue of Internet-of-Things

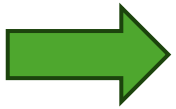


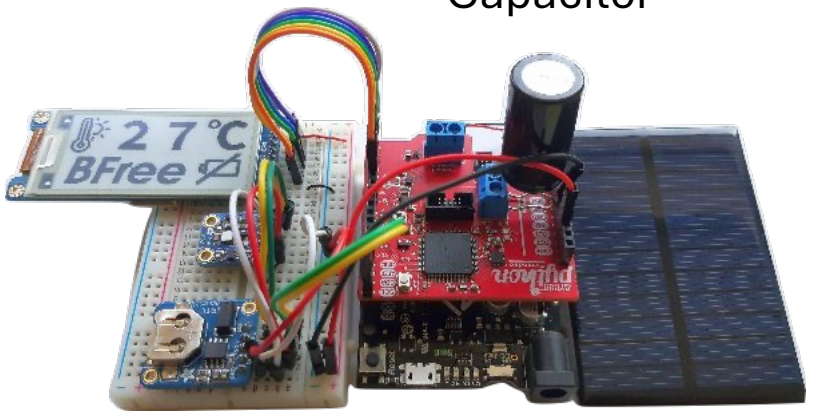
Microcontroller with sensors and communication components

Battery: hard to maintain, not resilient, not environment-friendly

Sustainable IoT with battery-free devices







Capacitor

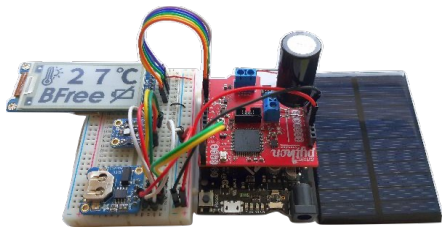
Solar panel, or other
energy-harvesting devices

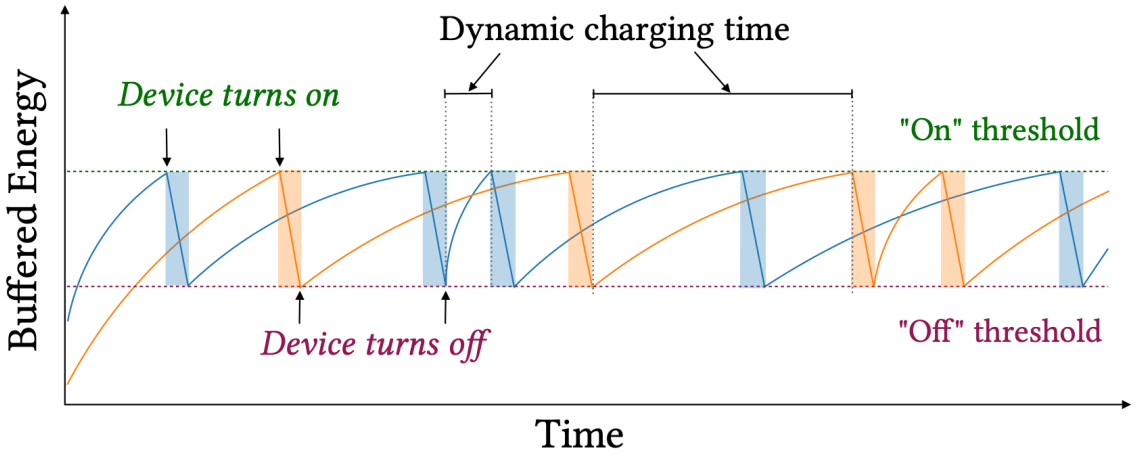
Sustainable: (almost) maintenance-free, more environment-friendly

Intermittency with battery-free devices

- Characteristics of battery-free devices
  - Small capacitors
  - Working time is tiny (ms level)
  - Charging time varies (from few ms to seconds or minutes) depending on the ambient energy conditions
- Intermittent computing!

Why tiny?

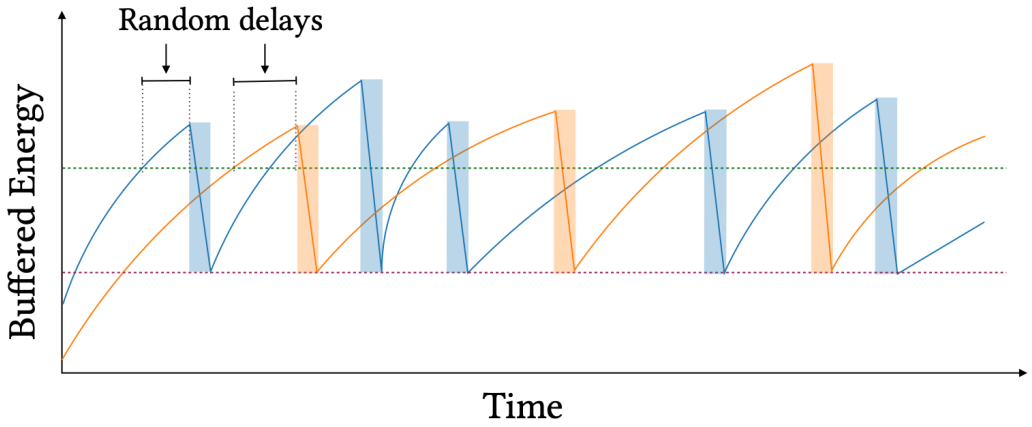




Challenges in device discovery

How can two devices meet and talk to each other?

- Find/Flync (NSDI'21)
  - Applying random delays to the charging time to increase encounter probability
  - Hard to tune, not efficient under random charging times
- Swift (TMC'24)
  - Based on number theory: linear congruential generator
  - Only works with static charging times



$$X_{n+1} = (aX_n + c) \mod m$$

where X is the sequence of pseudo-random values, and

m, $0 < m$ — the "modulus"

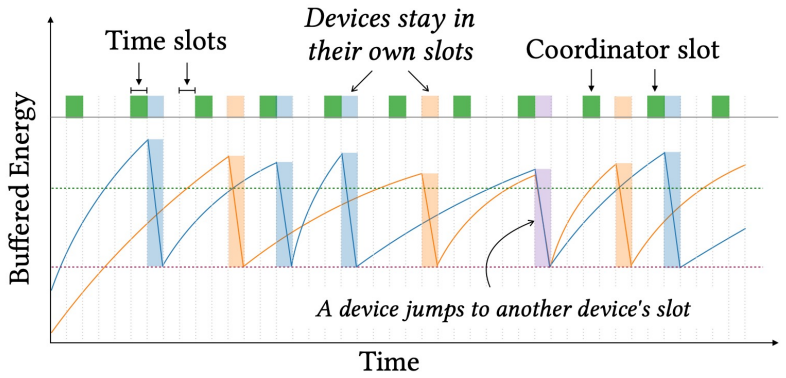
a, $0 < a < m$ — the "multiplier"

c, $0 \leq c < m$ — the "increment"

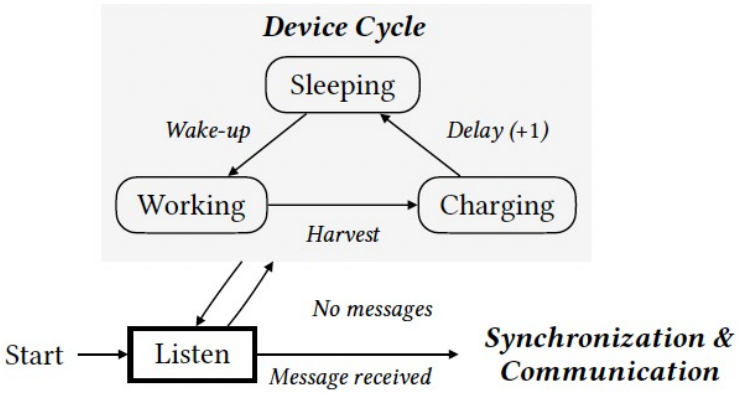
X_0, $0 \leq X_0 < m$ — the "seed" or "start value"

Our motivation

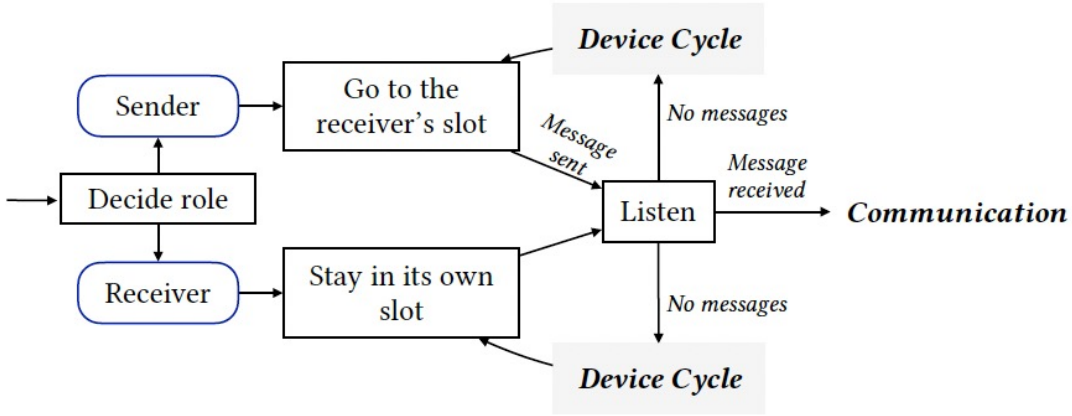
- **Complete randomness** (in charging times) complicates communication protocol design for battery-free IoT
- **A little artificial certainty** turns out to help significantly
- Our idea: one or a few battery-powered devices as **coordinators**, acting as a pulsar for battery-free devices



Our proposal: Pulsar



(a) Coordinator discovery

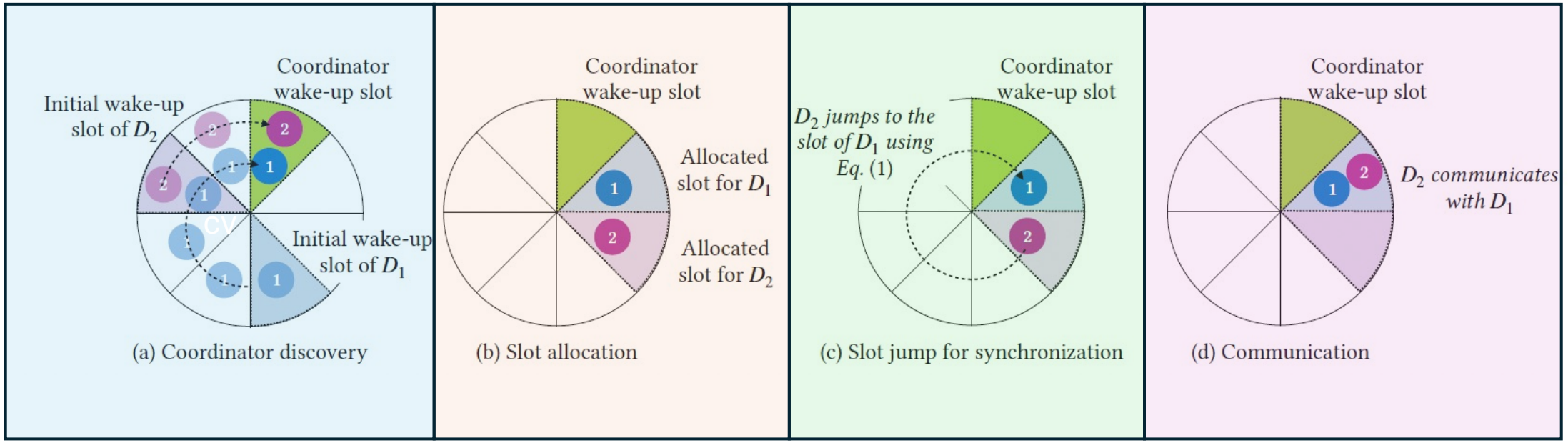


(b) Synchronization and communication

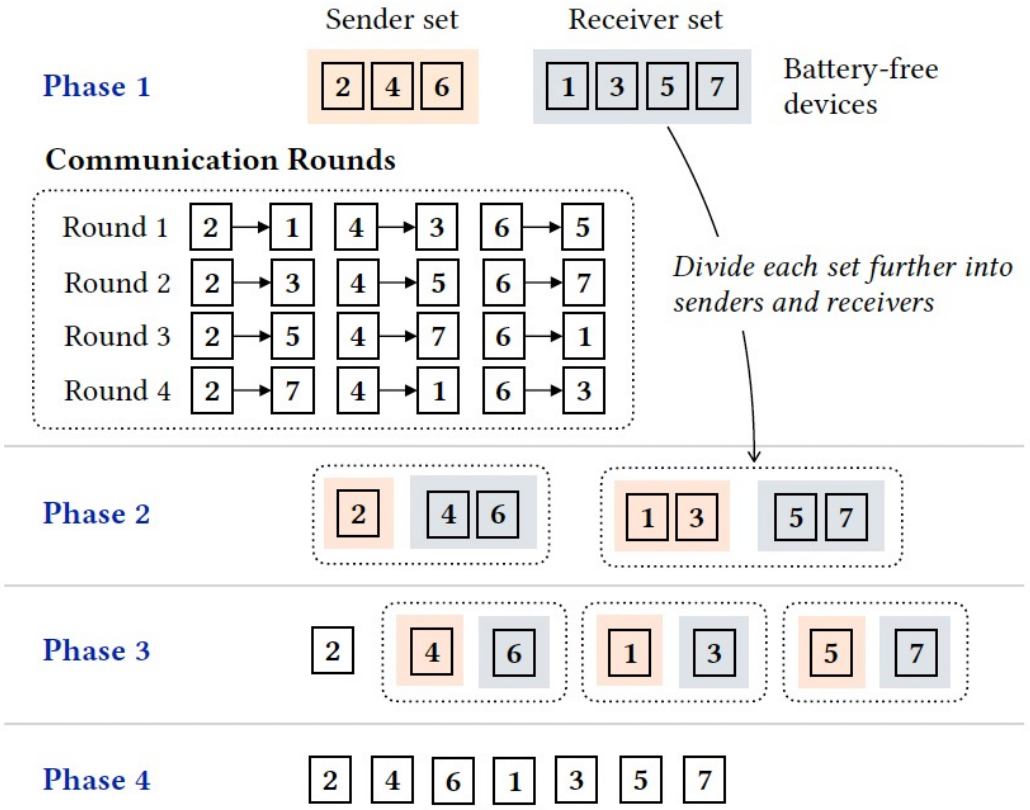
Step 1: battery-free devices discover the coordinator and obtain slot allocations

Step 2: battery-free devices use the allocated slots to communicate with each other

Pulsar procedures



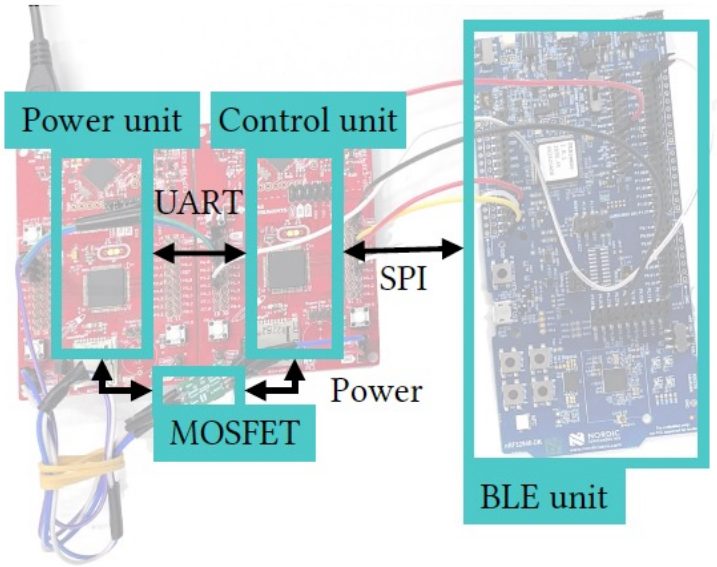
Example: all-to-all communication pattern



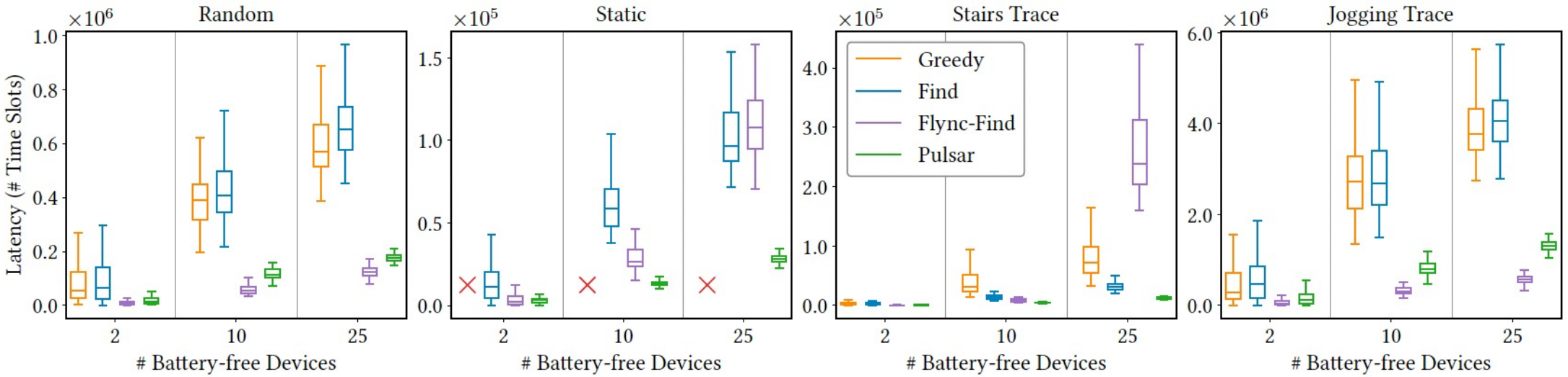
Each device will communicate with any other devices exactly once following a fixed schedule; use parallel communications to improve efficiency

Implementation and setup

- Simulations
  - Metric: all-to-all communication latency
  - Baselines: Greedy, Find, Flync-Find
  - Energy traces: real-world and synthetic
  - Number of devices: 2, 10, 25
  - Number of coordinator: 1
- Testbed (MSP430+nRF52840+MOSFET)
  - Baseline: Find
  - Energy traces: real-world
  - Number of devices: 2



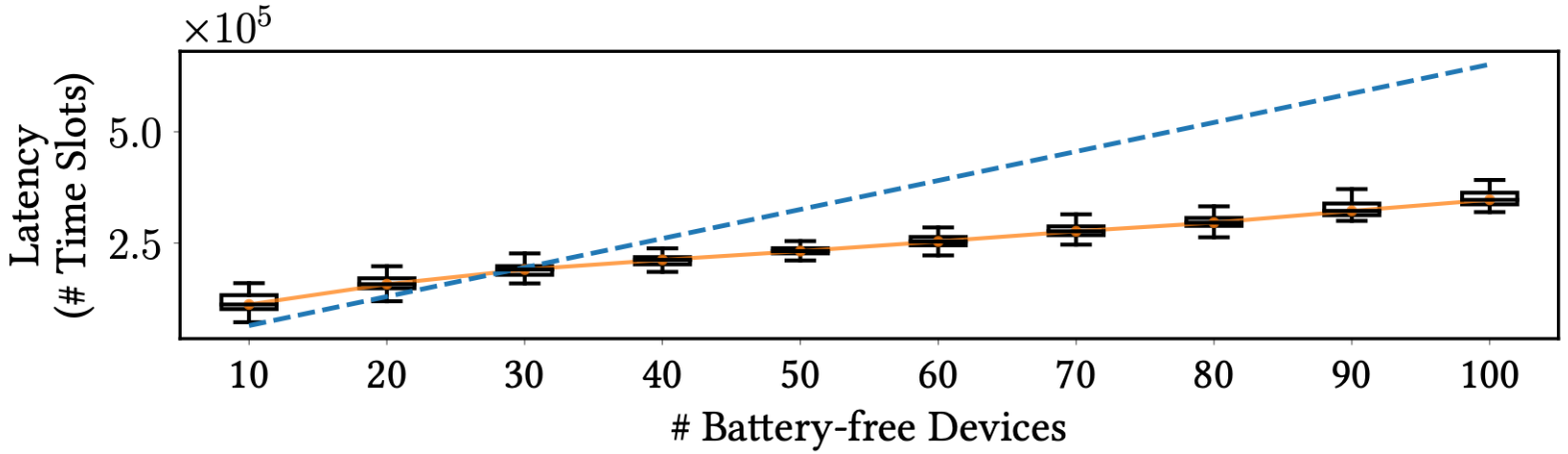
All-to-all communication latency



Communication time reduction: **2.5x** (25 devices, Stairs trace), **5.6x** (2 devices, Jogging trace)

Note: comparison unfair to Pulsar since baselines do not follow the same structured all-to-all pattern

Scalability study



Median latency grows sub-linearly owing to our **parallel communication rounds**

Baseline: the ideal linear scaling line is normalized against the two-device case

Summary

- **Device discovery and synchronization** is a **hard** problem for sustainable battery-free IoT systems
- We propose Pulsar, a system that **introduces little certainty,** with a small number of battery-powered coordinators, to **simplify** the problem and **accelerate** the process
- Preliminary results show the potential, but more complex communication patterns are still open to explore

Thanks! Questions?