Leaf-Link: Experiences Deploying Battery-Free Wireless Forest Sensing

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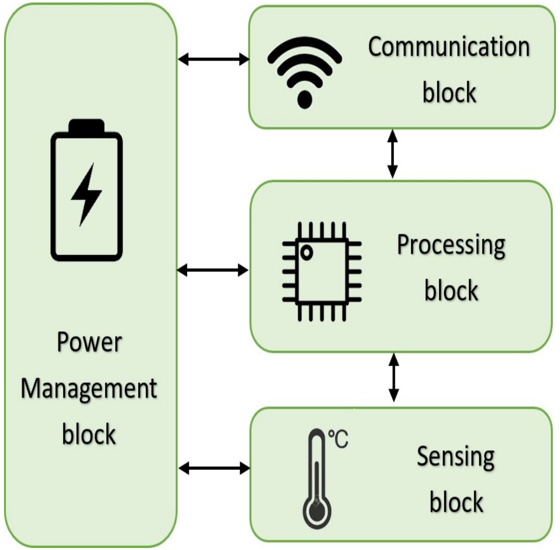
Why Energy Harvesting? [1/2]

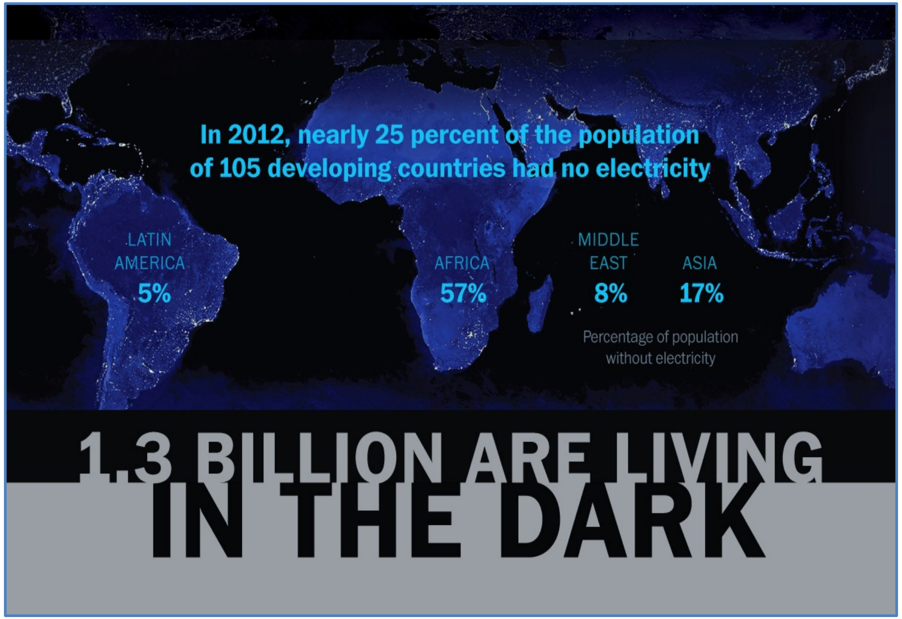


A simple architecture of IoT node

Everything relies on the power block

Batteries: limited life, infinite waste

Why Energy Harvesting? [2/2]



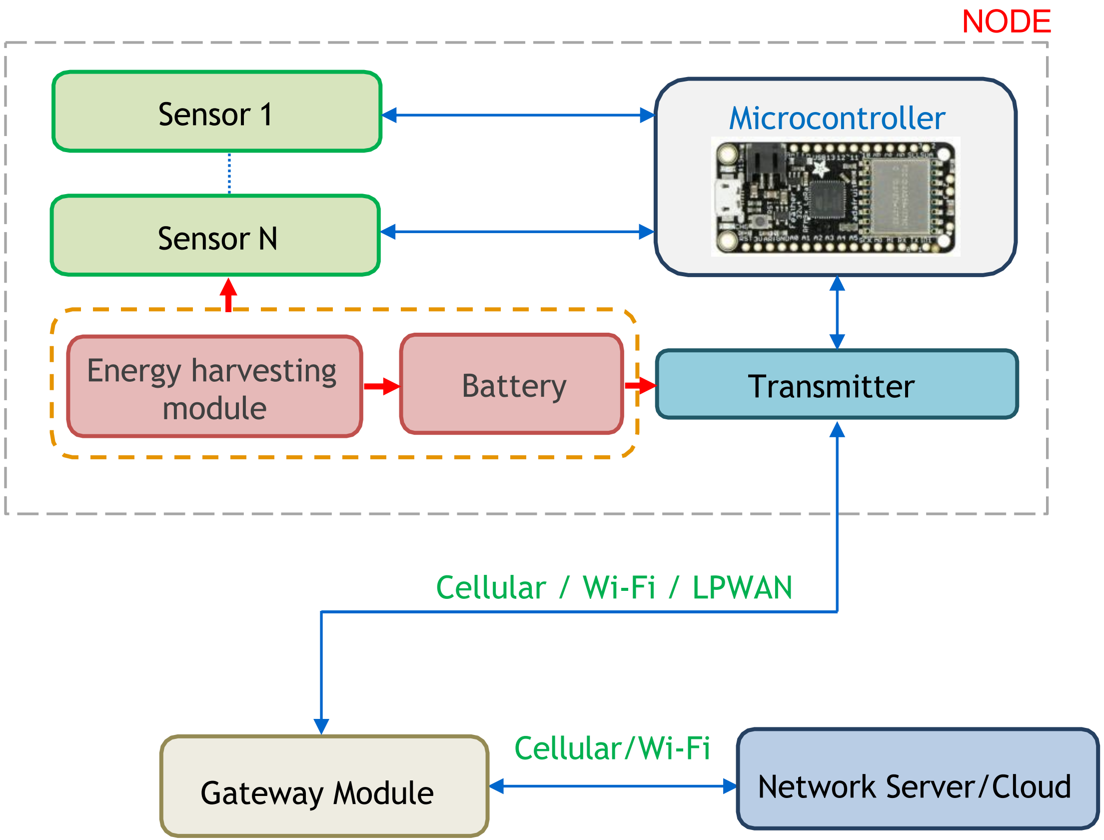
Resilient communication devices in areas with unreliable electricity infrastructure

Reliable data collection/monitoring in flood-prone & remote environments e.g. Vietnam

Source: The Washington Post, November 6, 2015

Is **Battery-Free** IoT Device Possible?

Modified IoT Node Architecture



Source: Hughes. et al., ***Gridstix: supporting flood prediction using embedded hardware and next generation grid middleware***, *WoWMoM'06*

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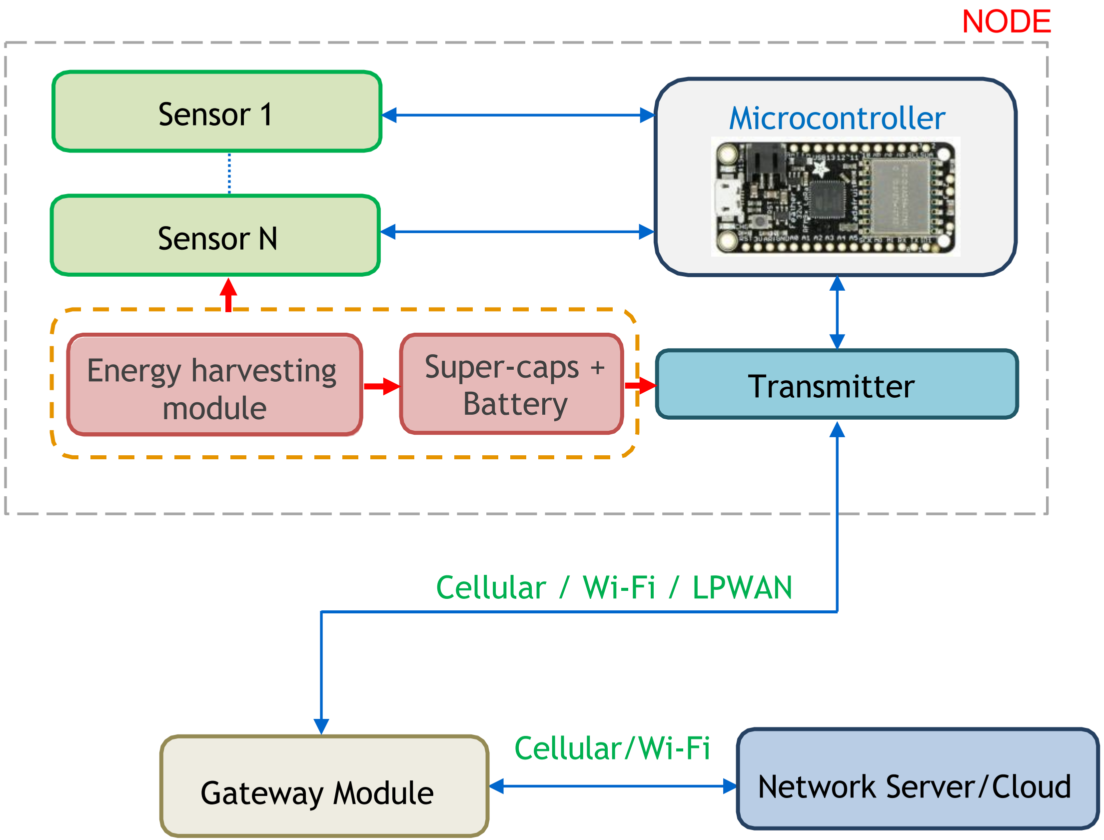
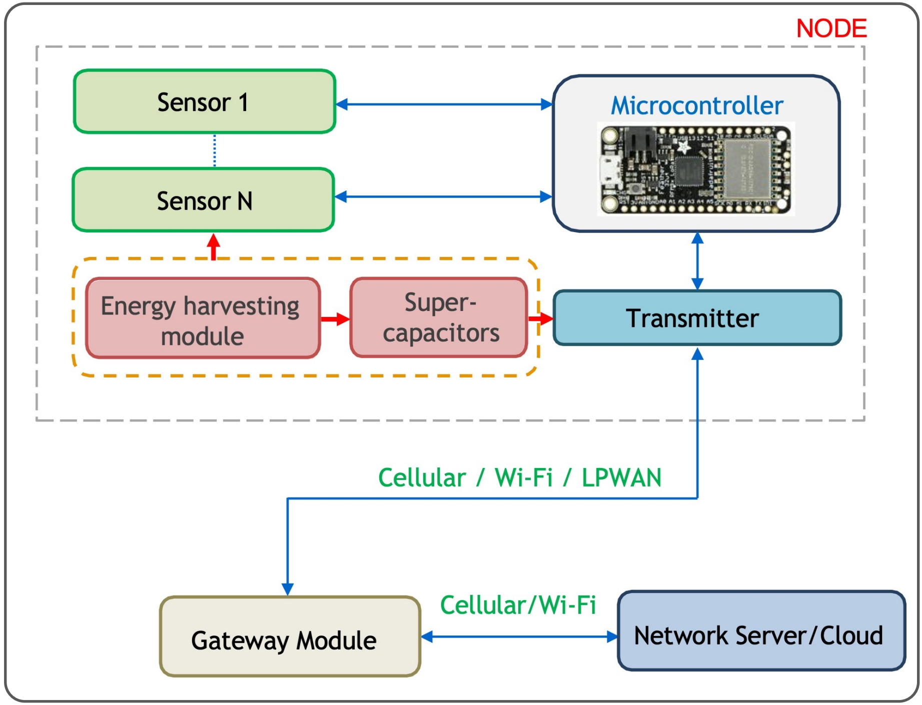
Modified IoT Node Architecture



Source: A.S. Thangarajan et al., Hybrid Perpetual Sensing Platform (HyPer), IoT'20

Modified IoT Node Architecture



Source: F. Yang et al., AsTAR: Sustainable Battery Free Energy Harvesting for Heterogeneous Platforms and Dynamic Environments, EWSN '19

Does this Solves Everything?

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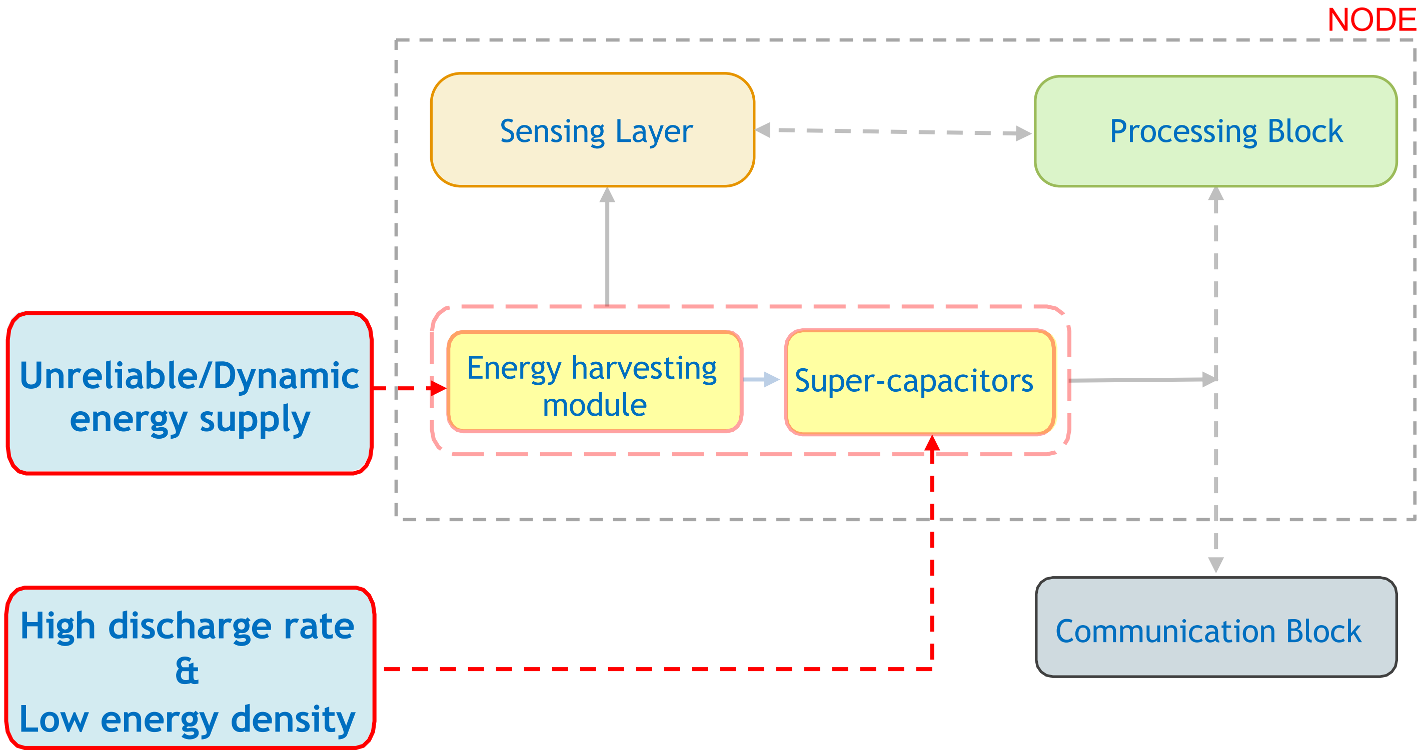
Battery-free EH IoT Node: The Pain Points



- *Additionally, most existing solutions are **integrated**, with*
- *poor or no **3rd party support***

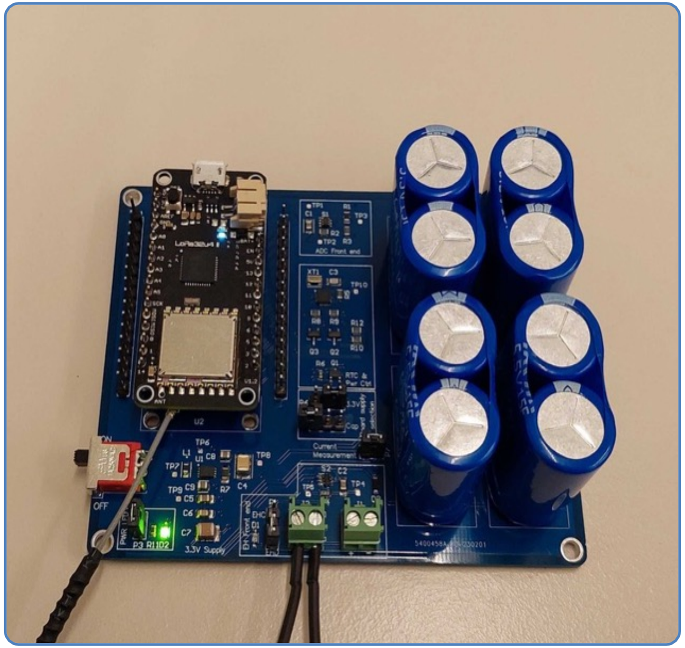
Flute: A Plug And Play Battery-free Wireless Sensing Platform

Modular and Compact Design for portable and mobile applications

Plug-and-Play Support for various IoT boards

Intelligent Charge Management Libraries

Ultra Low-cost Power, Battery Free and Energy Harvesting operation



Flute Power Board

› Takeaway:

Flute transforms commodity IoT boards into Battery-free Energy Harvesting devices

② How **reliable and efficient** can battery-free wireless systems be in the field?

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SoTA: Real-World Experiences

Mithræum of Circus Maximus [3, 17]:

- Deployed Battery-free EH sensors
- Intermittent computing → nodes failure tolerated

Findings:

- ***Kingdom*** *(battery baseline):* 71% uptime
- ***Republic:*** 22% yield of baseline; high failure rates, high peripheral energy cost
- ***Empire:*** HW/SW improvements; 25% yield

Limitation: Availability far below application needs (e.g. forest, mining, wildlife monitoring)

Gap: Real-world EH deployments are a few and lack continuous, reliable operation

Application Case: Forest Monitoring with Leaf-Link

Goal: Support research on forest microclimates and ecosystem dynamics using **BME680** sensor

Motivation:

- Climate change demands continuous, long-term environmental data
- Battery-based systems: **high maintenance**, **limited lifespan**

Challenges:

- Dense/seasonal canopy reduces solar energy availability
- Small energy buffer → risk of brownouts

The perfect place to compare batteries and super-capacitors

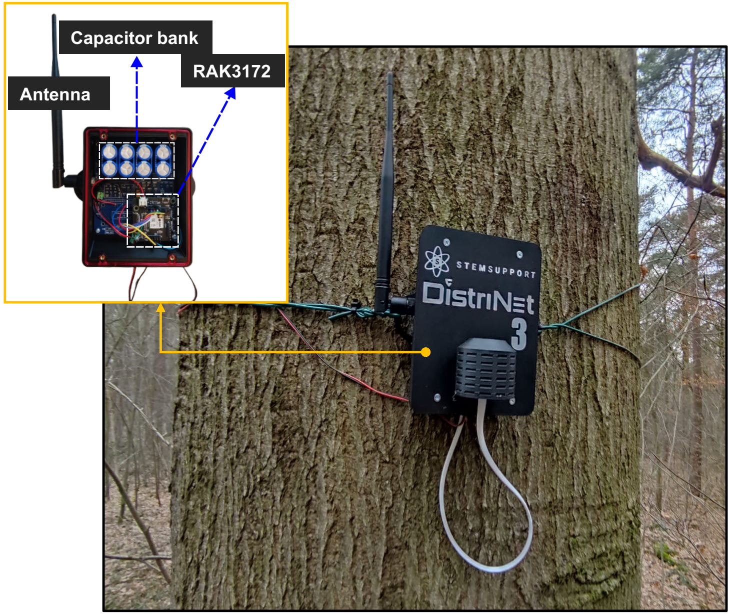
Leaf-Link

Scalable IoT Sensor Network with LoRaWAN Connectivity

Intelligent Charge Management Libraries

Battery Free and Energy Harvesting operation

Baseline for Long-Term Study



Leaf-Link Node

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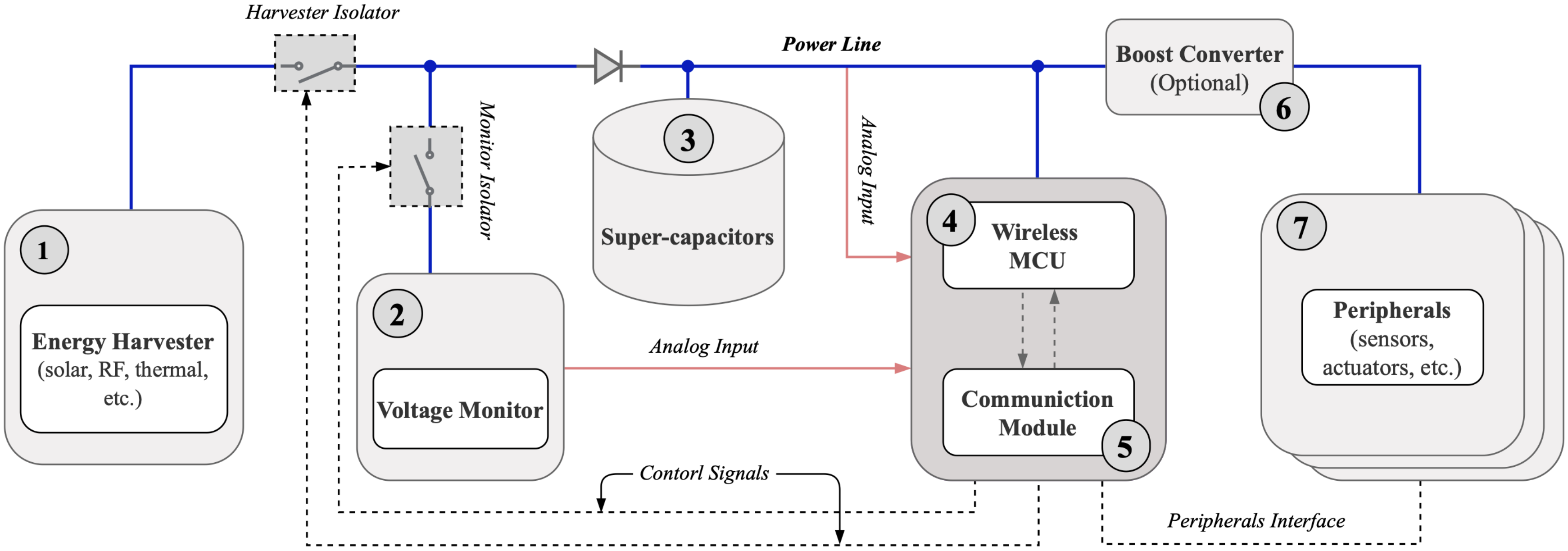
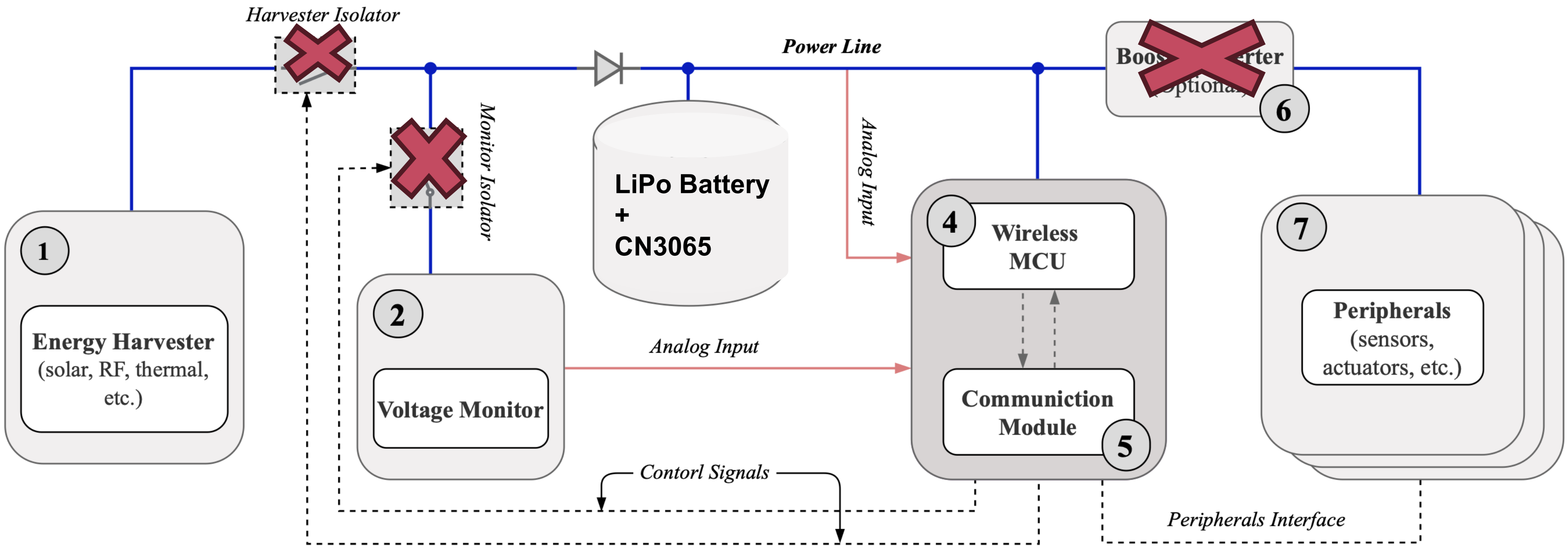
Hardware Architecture – Battery-Free



Built on FLUTE's Power Management Board

V.V. Bui et al., Flute: Enabling a Battery-free and Energy Harvesting Ecosystem for the IoT (MobiQuitous'23)

Hardware Architecture – Battery-Powered



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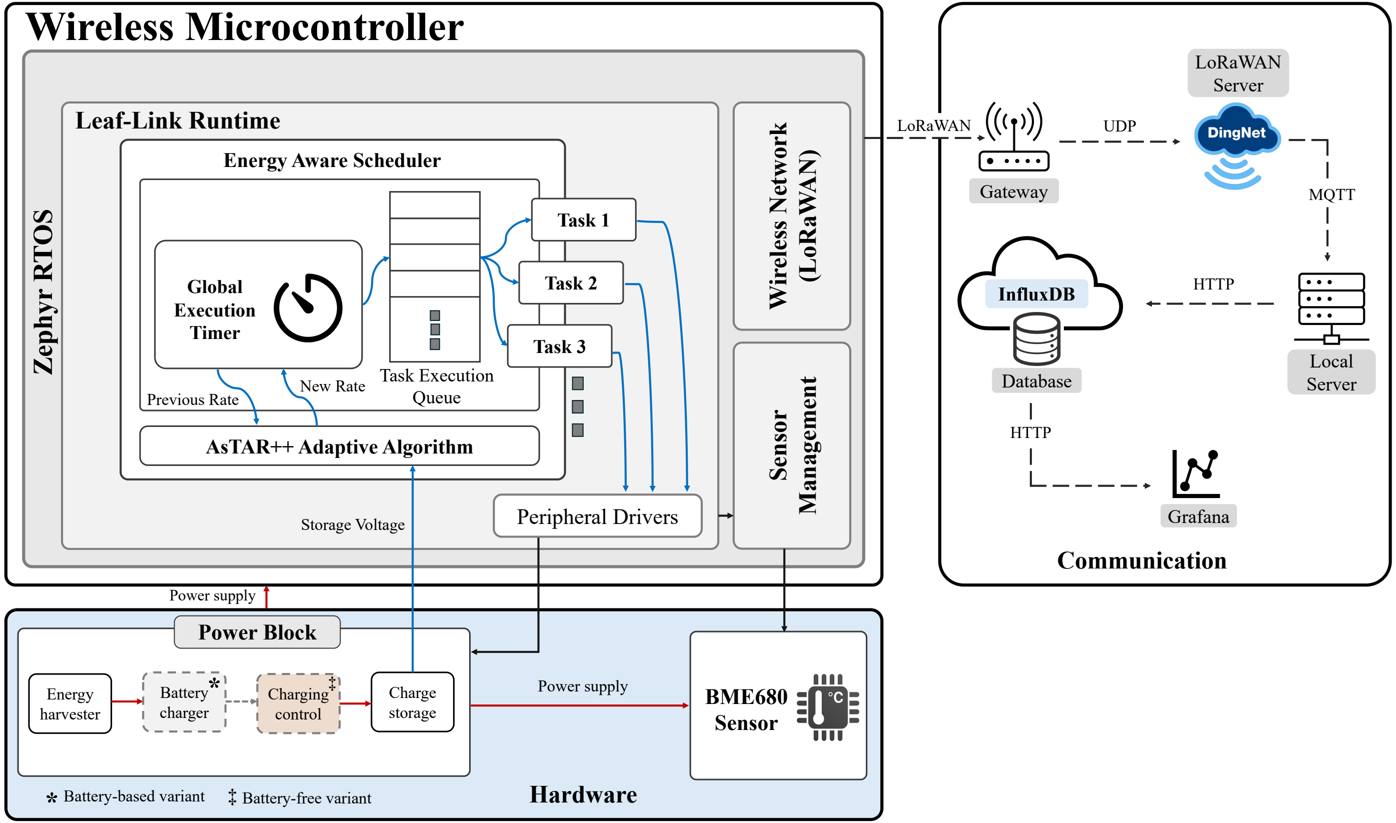
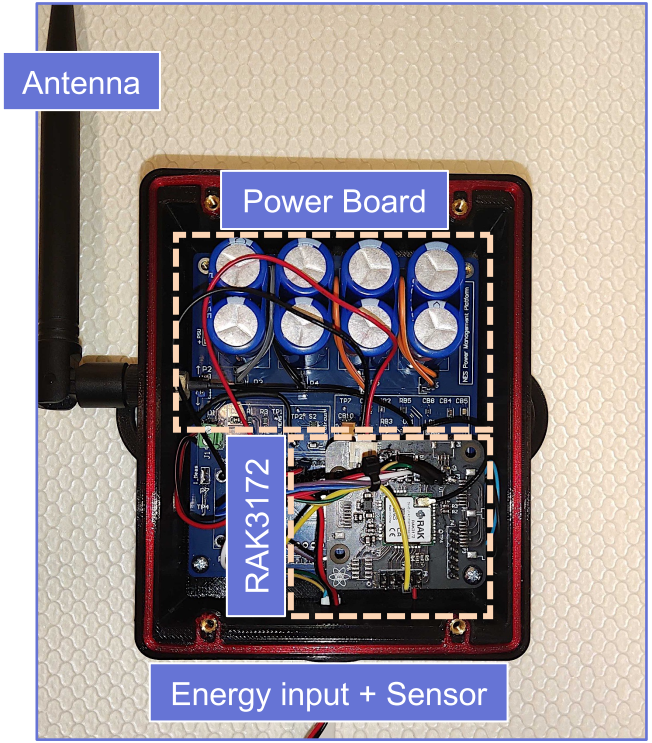
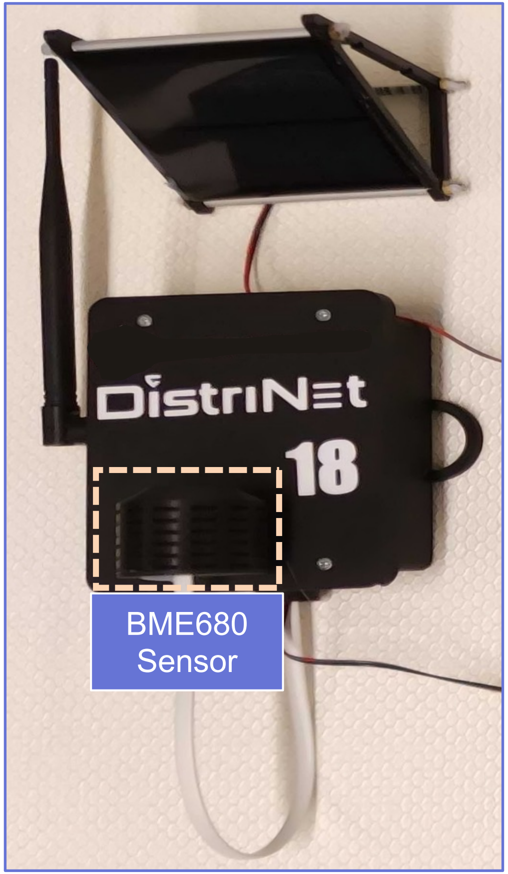
Software Architecture



Built on FLUTE's Adaptive Scheduler

Leaf-Link Reference Hardware





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Battery-Free vs. Battery-Powered

Feature	**Battery-Free Variant**	**Battery-Based Variant**
Storage	**4 × 15 F** super-caps (≈ **0.252 Wh**)	3200 mAh LiPo (≈ **11.84 Wh**)
Lifetime	Thousands of re(charge) cycles	Limited re(charge) cycle
Cost (10K units)	**~$21.88**	**~$8.72**
Charging management	• Open-circuit Vpv via control switch • HV cutoff at 5.4 V	• CN3065 linear charger • Adaptive current regulation

Takeaway:

- **Battery-free:** Long lifetime, sustainable, but lower energy capacity
- **Battery-based:** higher energy buffer, but shorter lifetime and measurement limitations

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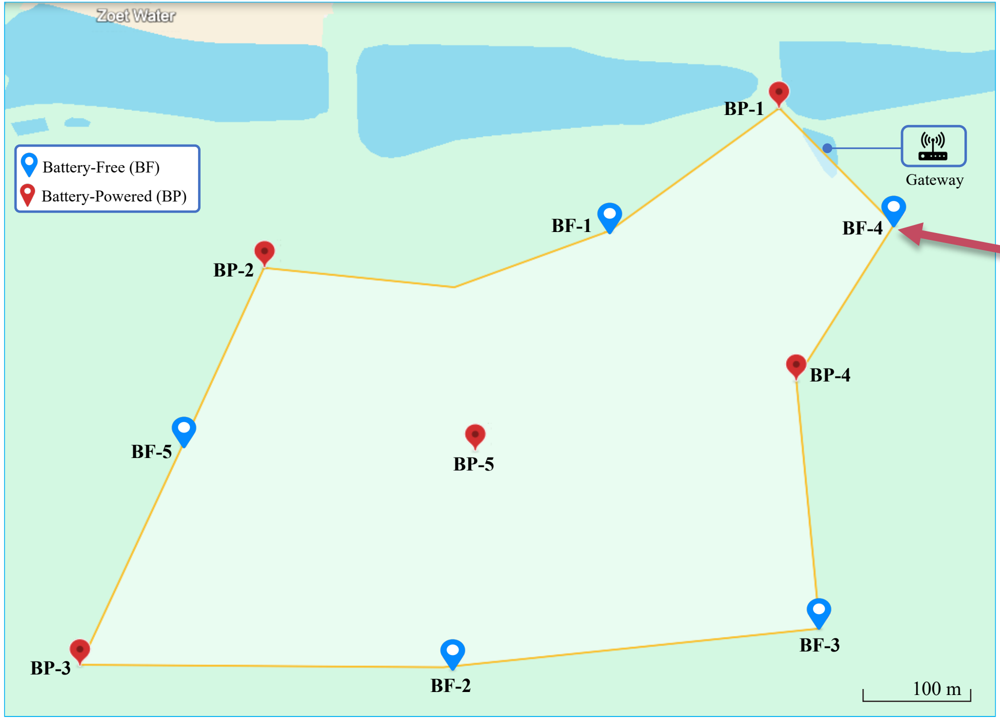
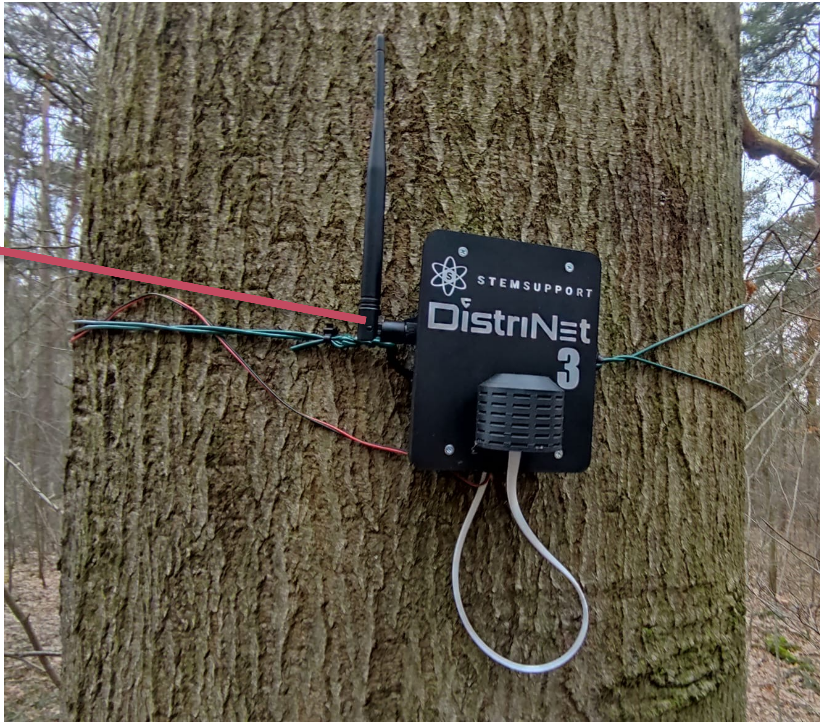
Deployment



Nodes distribution across the forest



A representative node

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③ Does Leaf-Link Deliver Reality?

Lesson 1: Battery-free does not mean lower reliability

› Failure Modes:

- **Software Failure** = Node crashes or Network has failed
- **Power Failure** = When node brown-out

	Battery-Free (BF)	Battery-Powered (BP)
Software Failure	BF-3, BF-4	BP-1, BP-2, BP-5
Power Failure	BF-3: 16 h (then SW bug) BF-5: <9 h	BP-1: depleted after 2 weeks (no recovery) BP-4: brown-out before end
Recovery	Fast recharge (✓)	Requires ≥4.65 V to charge
Efficiency	Uses almost all harvested energy	~2% energy loss near full charge

› Findings:

- *Most of the SW failures are linked to the **radio problems***
- *Canopy-induced reduction in solar availability results in most **power failures***

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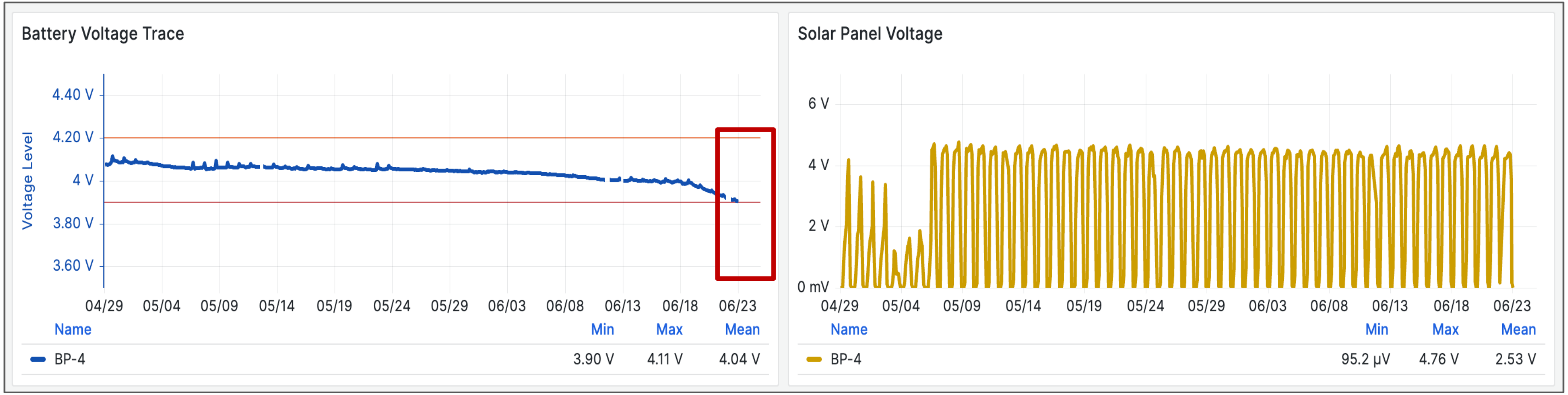
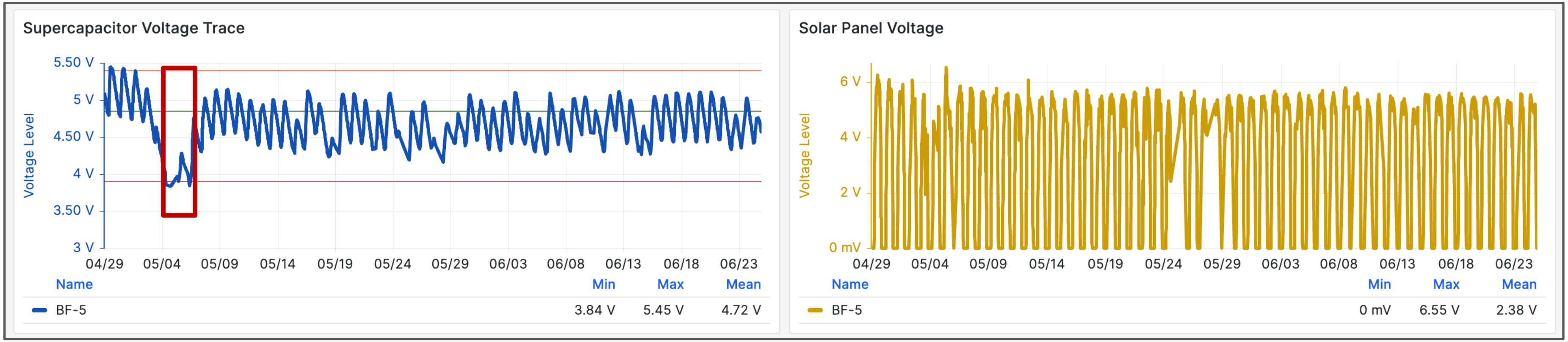
Lesson 1: Battery-free does not mean lower reliability



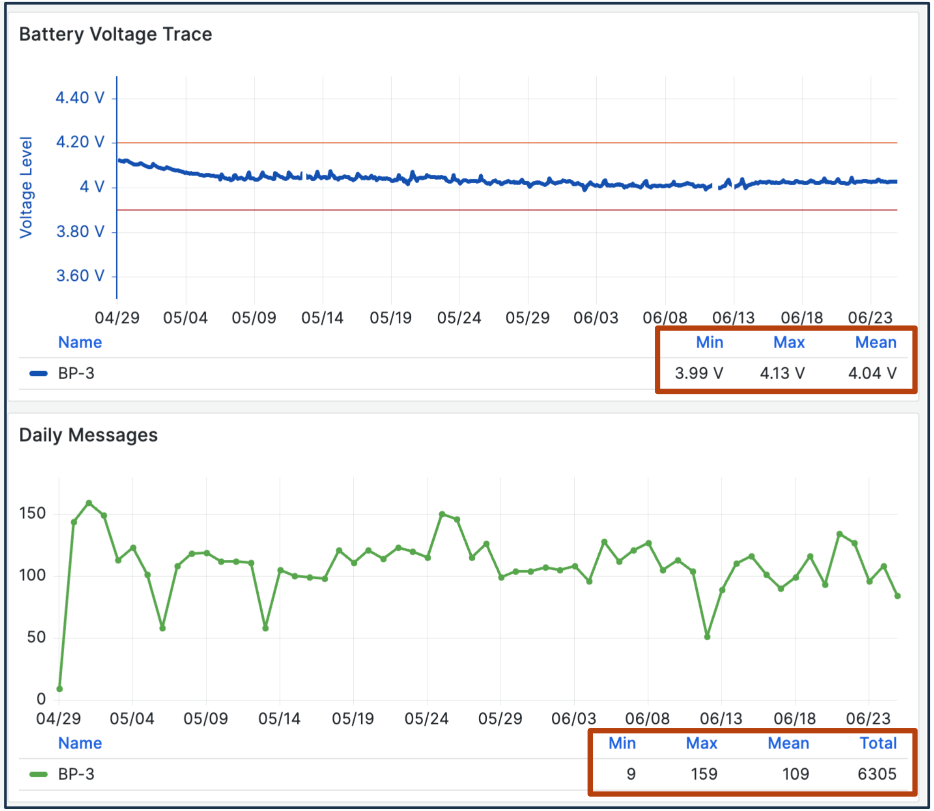
Battery-Powered Sensor Node



Battery-Free Sensor Node

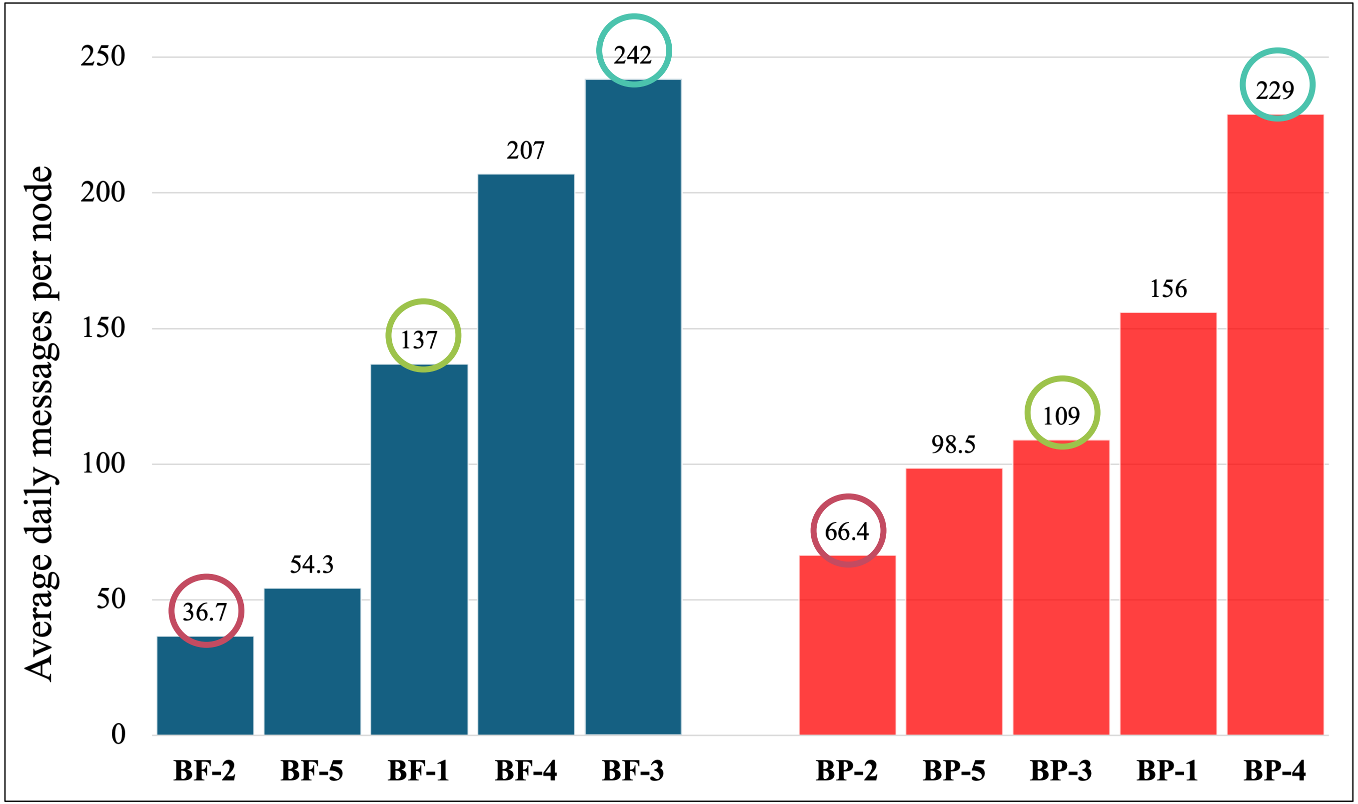
Lesson 2: Battery-Free Devices Are Efficient

Battery-Free Sensor Node

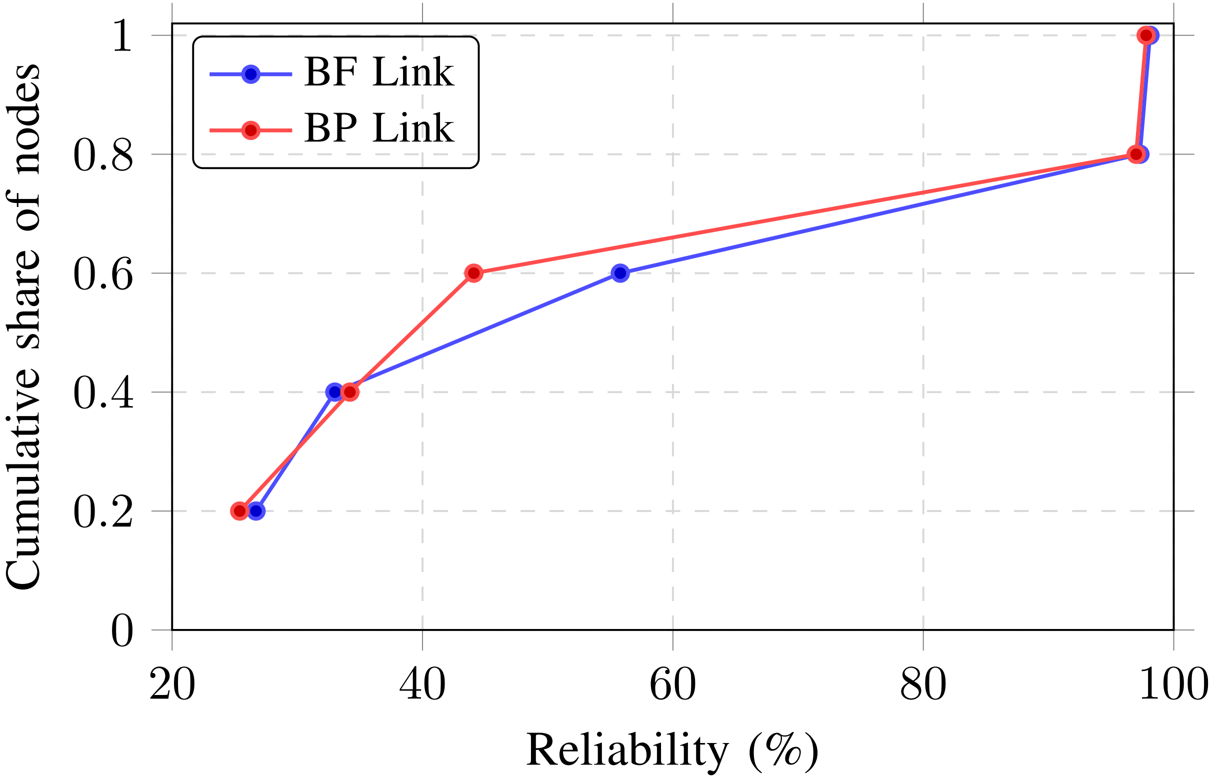


Battery-Powered Sensor Node

Lesson 2: Battery-Free Devices Are Efficient



Lesson 3: LPWAN Reliability is Low in Forest Environments



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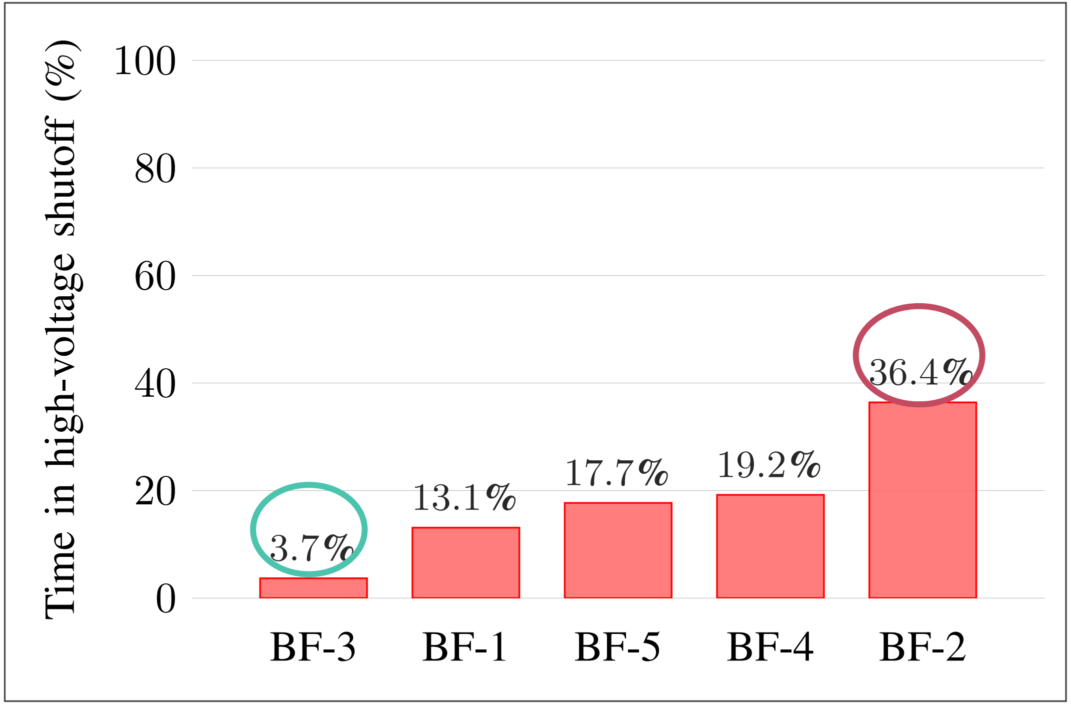
Lesson 4: Energy subsystem dimensions drive efficiency

› **Inefficiency sources:**

- *Under-utilised solar energy*
- *Conservative scheduling*



High-voltage shut-off mode distribution for BF nodes

› **Takeaway:**

Proper dimensioning of energy subsystem is critical for efficiency

Conclusion

› **A 2-month forest deployment of Battery-Free (BF) vs Battery-Powered (BP) nodes**

› **Findings:**

- *BF > BP in reliability → **fewer failures, faster recovery***
- *BF > BP in efficiency → **more frequent message transmission***
- *BP limited by **charging inefficiencies** (blocked at low V/I)*

› **Future Work:**

- Extend deployment to capture seasonal effects
- Scaling network: 10 to 100 nodes
- Deploy in diverse environments & workloads for generality

› **Takeaway:**

Adaptive, battery-free design enables long-term, low-maintenance wireless sensing

Funding Support & Award

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Thank you for Listening!

Q&A

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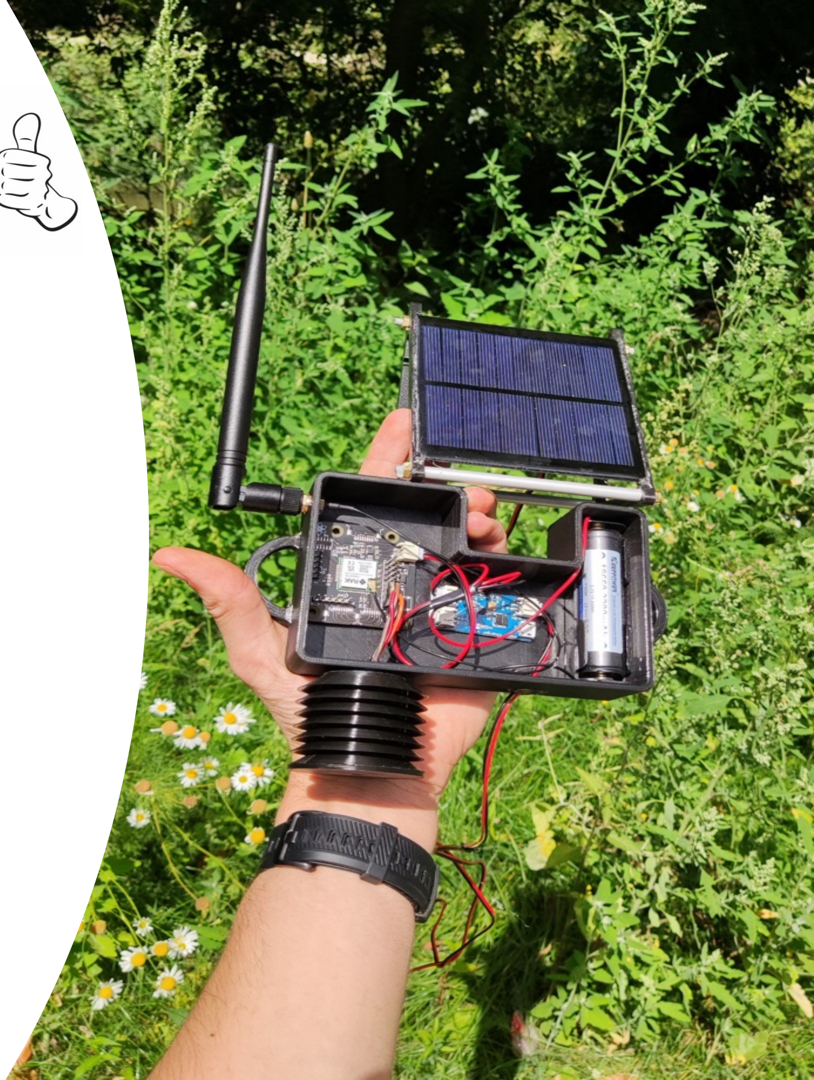

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Backup slides

Leaf-Link Hardware Configurations

RAK3172		
MCU	STM32WLE5CCU6	
Network	LoRaWAN	
Processor	Cortex-M4	
Speed	48 MHz	
Radio	LoRa	
OS	Zephyr v3.x	
SOLAR CELL	**Voltage**	**Current**
	6.0 V	250 mA
SUPER-CAPACITOR	**Voltage**	**Capacitance**
	5.5 V	60 F
Current at Optimum V	**Sleep**	50 μA
	Wake	13 mA
	Transmit	80 mA

Common Software Configurations

Task Scheduler	**daytimeMaxRate**	5 min
	minRate	2 h
	nightMaxRate	5 min
Energy Thresholds	**vMax**	5.4 V
	vOptimum	4.15 V
	vMin	3.9 V
LoRa Radio	**Frequency**	868 MHz
	Bandwidth	125 kHz
	Spreading Factor	12
	TX Power	14 dBm
	Coding Rate	4/5