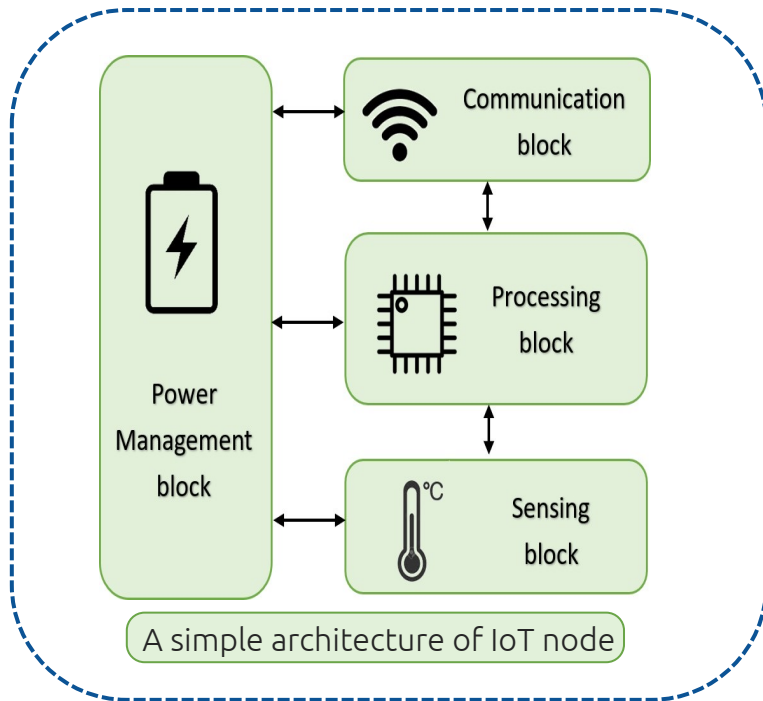


Leaf-Link: Experiences Deploying Battery-Free Wireless Forest Sensing

Shuaibu Musa ADAM, Van Vu Bui, Lowie Goossens, Sam Michiels, Ka Lok Man and Danny Hughes

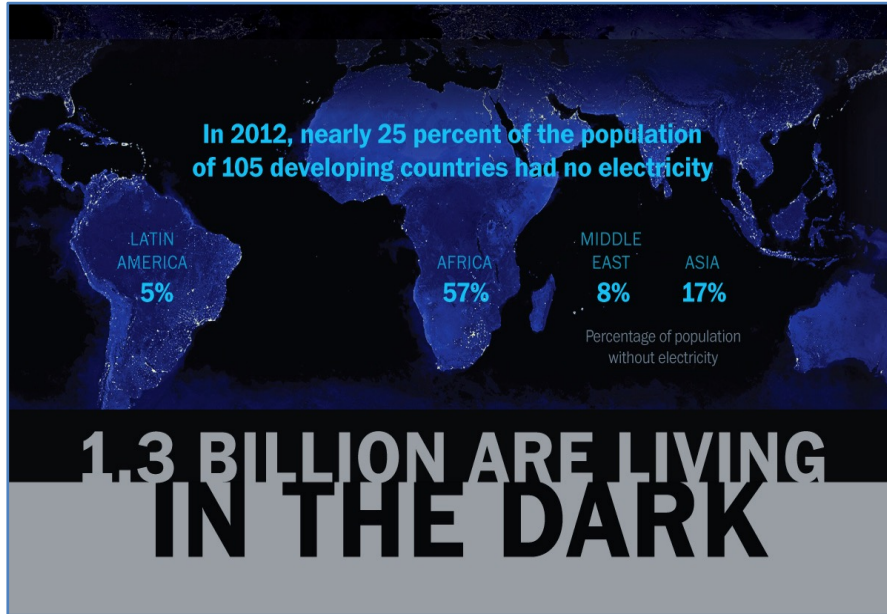
PhD Student, DistriNet, KU Leuven, Belgium

shuaibumusa.adam@kuleuven.be



Everything relies on the **power block**

Batteries: limited life, infinite waste

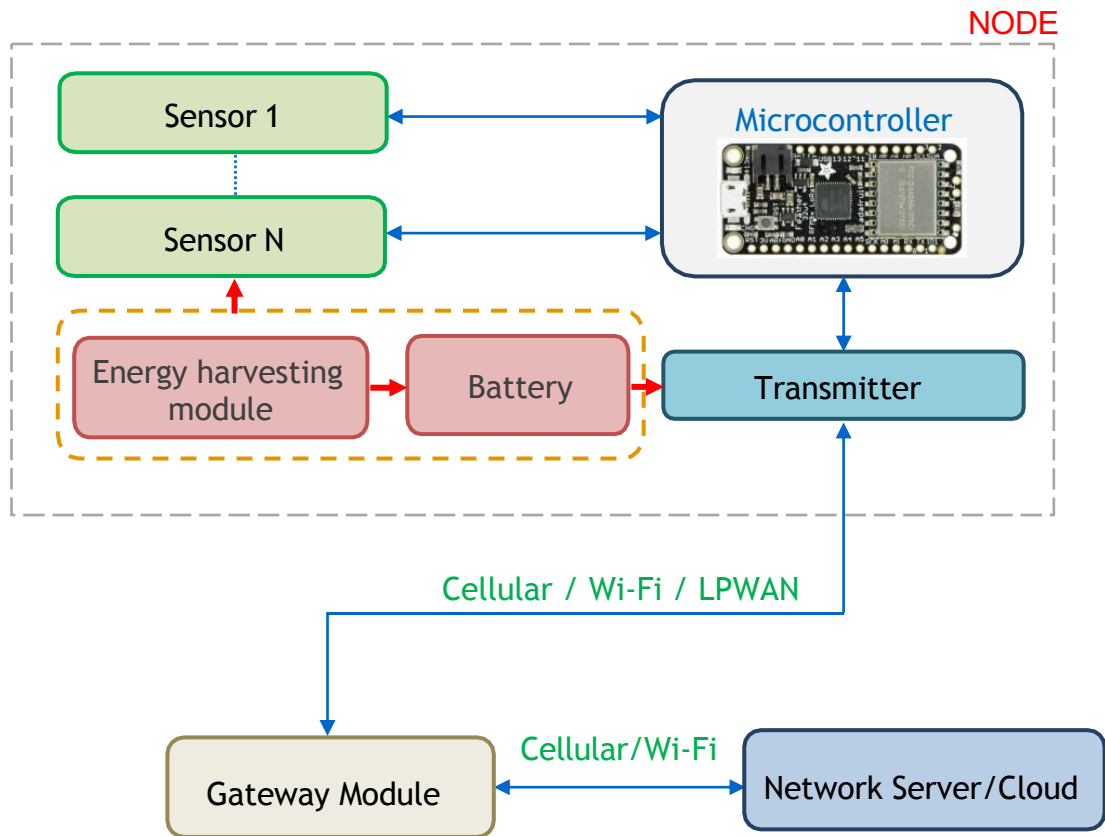


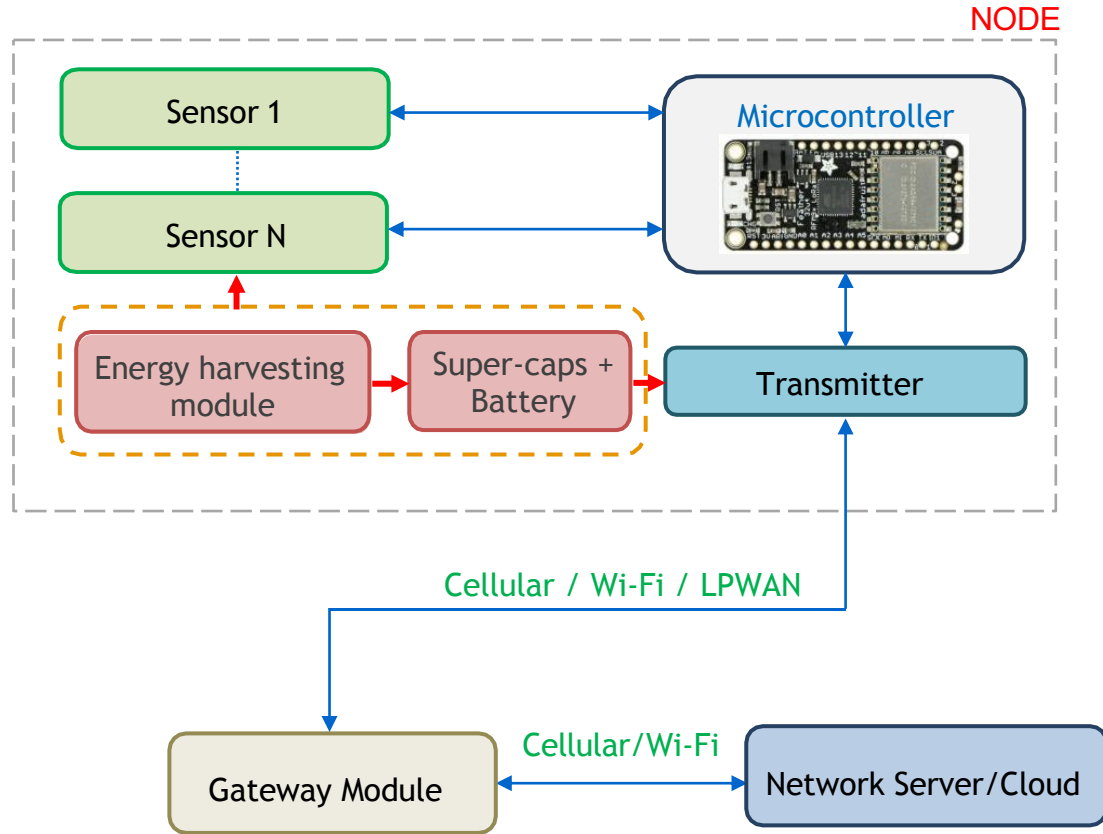
Resilient communication devices in areas with **unreliable electricity infrastructure**





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





AsTAR: Sustainable Energy Harvesting for the Internet of Things through Adaptive Task Scheduling

FAN YANG, Research In KU Leuven, Belgium
ASHOK SAMRAJ THA GOWRI SANKAR RAJ, Department of Technology
WOUTER JOOSEN

Battery-free Internet-of-Things (IoT) research remains complex to develop ability and dynamic energy-aware task scheduling energy. AsTAR enables the or a weighted combination requiring no *a priori* mode capability to efficiently de dynamic environmental ce AsTAR guarantees *Sustain* acts quickly to environme resources following the de minimal performance over CCS Concepts: • **Comput and platforms**; **Wireless int software**;

Additional Key Words and ACM Reference format:
Fan Yang, Ashok Samraj T 2021. AsTAR: Sustainable I ACM Trans. Sen. Netw. 18, <https://doi.org/10.1145/346>

Extended version of EWSN'19 and Dynamic Environment? This research is partially fund Authors' addresses: F. Yang, I Shanghai, China and imec-Di and D. Hughes, imec-DistriN wouter.joosen@kuleuven.be, c University of Technology, 2 G Permission to make digital or provided that copies are not n the full citation on the first p Abstracting with credit is perri port specific permission and/ © 2021 Association for Comp 1550-4859/2021/10-ART4 \$15.0 <https://doi.org/10.1145/346789>

ACM

Flute: Enabling a Battery-Free and Energy research

Van Vu Bui^{1,2(✉)}, Shua Ashok Samraj Thang Nelson Souto Rosa³, Hyun

¹ DistriNet, K
² Department of Engine
³ Centro de I

Abstract. Nowadays, m ate on batteries, offering maintenance costs and ex nation with super-capacit considered complex and ut To address this problem, v tem for building battery-f focuses on transforming e free devices. Reliable ope generic power management sustainable operation in t We evaluate our approach scenarios and show that i reliable operation for a r using LTE-M and LoRa. I for building a battery-free

Keywords: Self-adaptive boards • Energy harvestin

1 Introduction

IoT research aims to create effi embedded devices can commu have resulted in the creation c tems (OS) [9] and network p Micro Controller Units (MCUs) However, the current ecosy has yet to assimilate recent res ing [EH] operation [9]. We ad

© ICST Institute for Computer Sciences, Published by Springer Nature Switzerland A. Zaslavsky et al. (Eds.), *MobiQuitous*, <https://doi.org/10.1007/978-3-031-63999-2>

Batteryless, energy-harvesting systems could reshape the Internet of Things into a more sustainable societal infrastructure.

BY SAAD AHMED, BASHIMA ISLAM, KASIM SINAN YILDIRIM, MARCO ZIMMERLING, PRZEMYSŁAW PAWELCZAK, MUHAMMAD HAMAD ALIZAI, BRANDON LUCIA, LUCA MOTTOLA, JACOB SORBER, AND JOSIAH HESTER

The Internet of Batteryless Things

IMAGINE USING a health bracelet that tracks your blood pressure and glucose level that you do not have to charge for the next 20 years. Imagine sensors attached to honeybees helping us understand how they interact with their environment or bio-absorbable pacemakers controlling heart rate for 6–8 months after surgery.

Whether submillimeter-scale “smart dust,”⁹²³ forgettable wearables, or tiny chip-scale satellites, the devices at the heart of the future of the Internet of Things (IoT) will be invisible, intelligent, long-lived, and maintenance-free. Despite significant progress over the last two decades, one obstacle stands in the

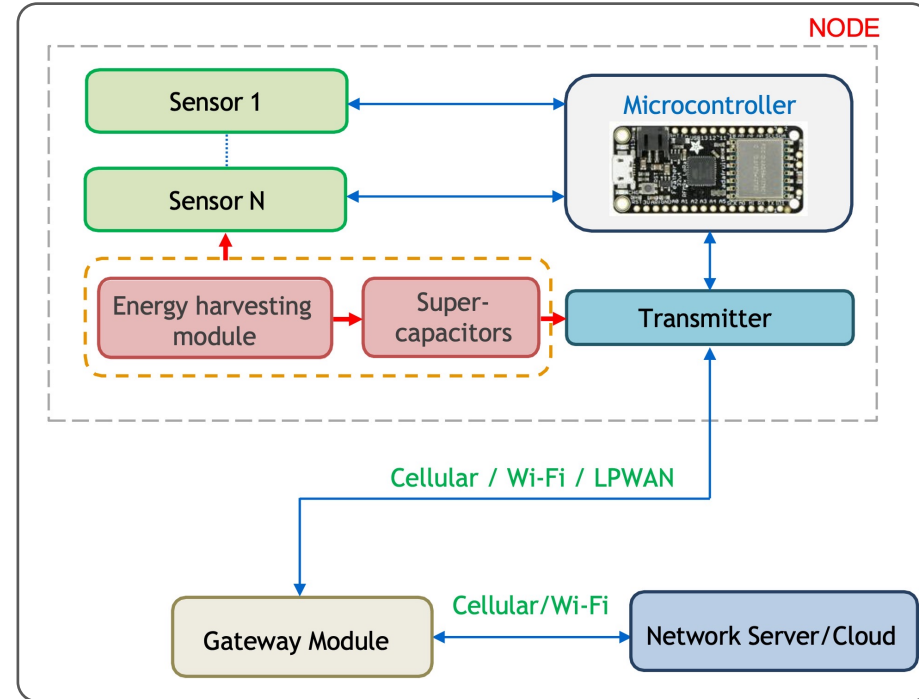
way of realizing next-generation IoT devices: the battery. Batteries provide the convenience of a reliable energy supply but create a host of problems. Batteries limit device lifetime and yield high maintenance costs. As device size continues to scale down, battery density scaling has not kept pace. As IoT device applications demand more computational capabilities, energy limits lifetime to weeks or months. Even rechargeable batteries have a limited lifetime, wearing out after 300–500 charge cycles. As we move toward a future with trillions of IoT devices,⁹ replacing trillions of dead batteries and devices will be both prohibitively expensive and irresponsible. A future IoT with trillions of new battery-powered devices would create an environmental catastrophe.

Most discarded batteries end up in landfills—only 5% are recycled. Discarded batteries release toxic fumes into the air and disperse chemicals in the soil as they break down. When batteries are recycled, the process releases contaminants into waterways.⁷ Batteryless devices and intermittent executions. During the last decade, and building on work from the decades prior, research pushed toward a new kind of system that is pervasively deployed,

a <https://bit.ly/691LLSNE>

» key insights

- As we move toward a future with trillions of IoT devices, replacing batteries will be both prohibitively expensive and irresponsible.
- Over the past decade, research produced new energy-efficient programming languages, compilers, runtime systems, and architectural designs that enable real-world applications of batteryless devices.
- Although existing work laid a foundation for batteryless, energy-harvesting computing, the field is arguably at a stage where a much bigger leap is needed for this technology to gain widespread adoption. We discuss six fundamental directions we maintain to be crucial for the field to thrive.

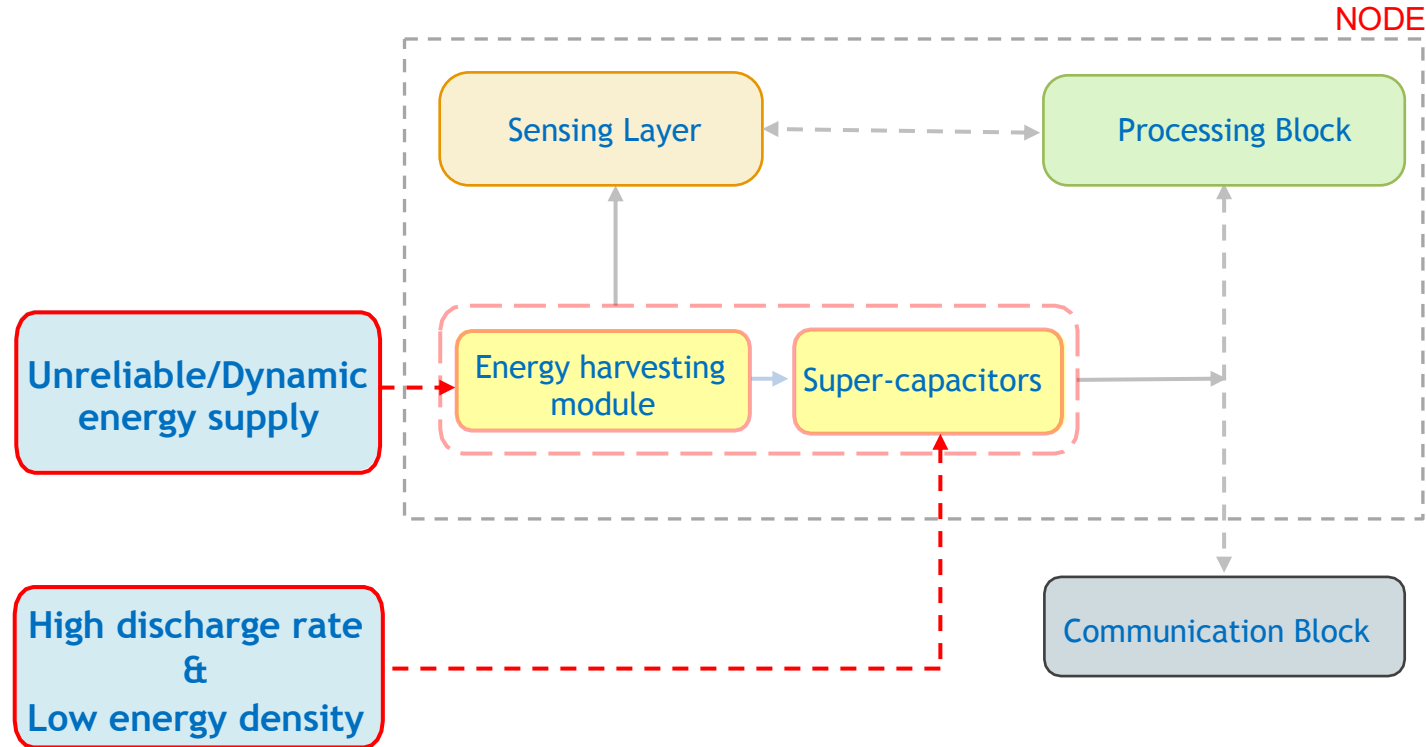


Source: F. Yang et al., AsTAR: Sustainable Battery Free Energy Harvesting for Heterogeneous Platforms and Dynamic Environments, EWSN '19



Does this Solved **Everything**?

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



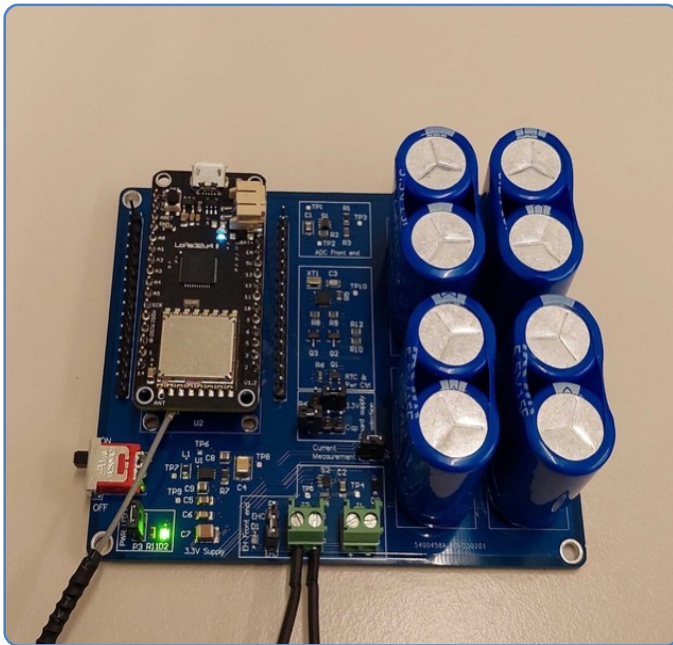
Plug-and-Play Support for various IoT boards



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?

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



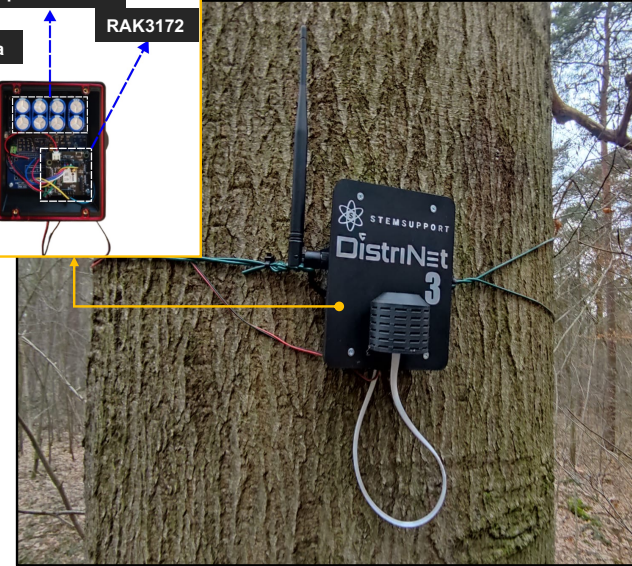
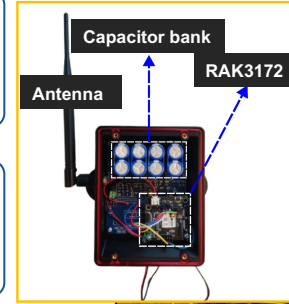
Intelligent Charge Management Libraries



Battery Free and Energy Harvesting operation

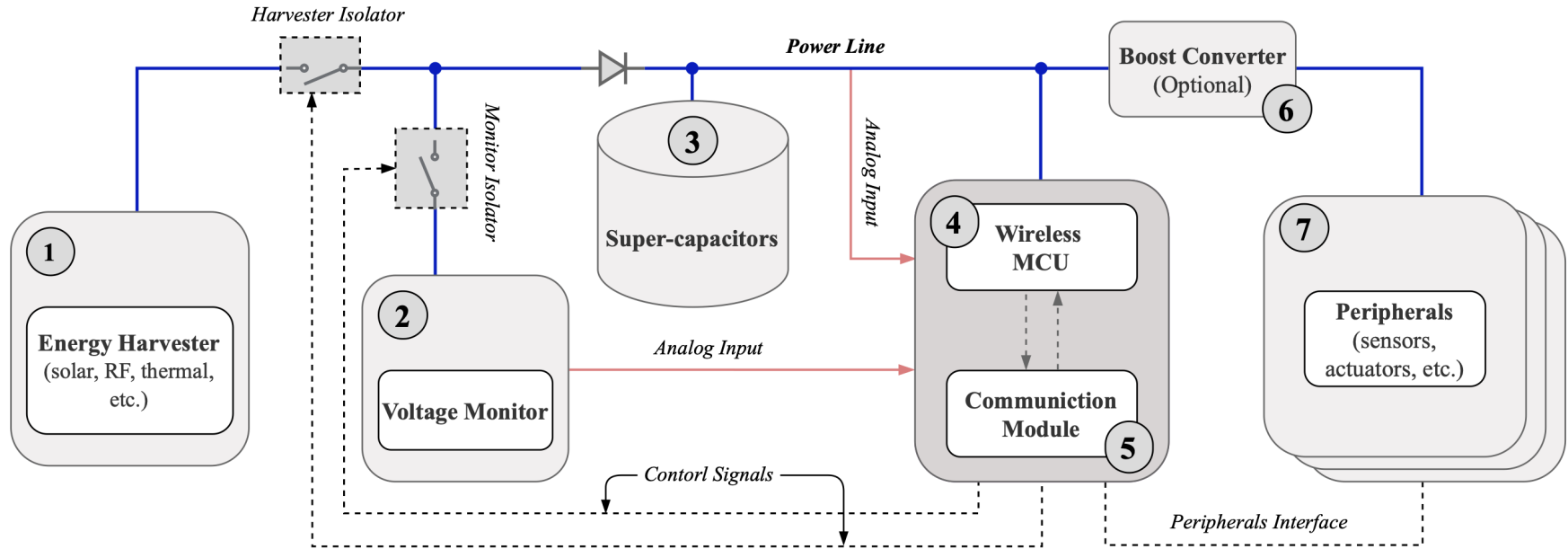


Baseline for Long-Term Study



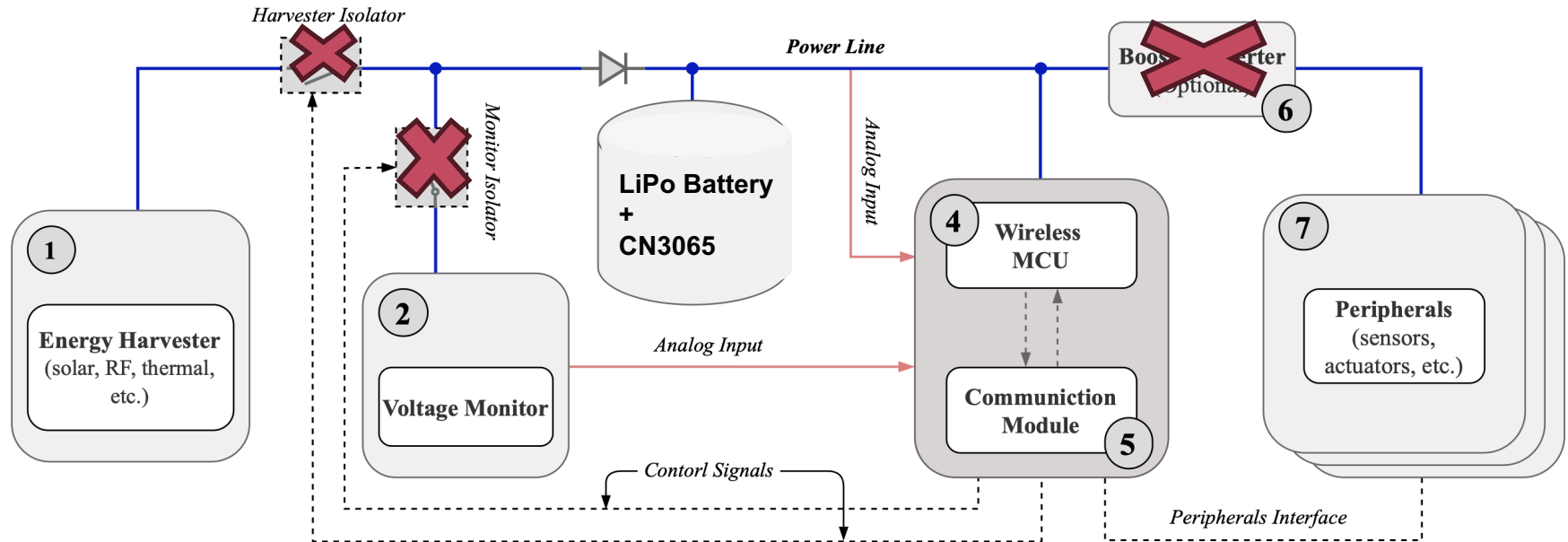
Leaf-Link Node

Hardware Architecture – Battery-Free

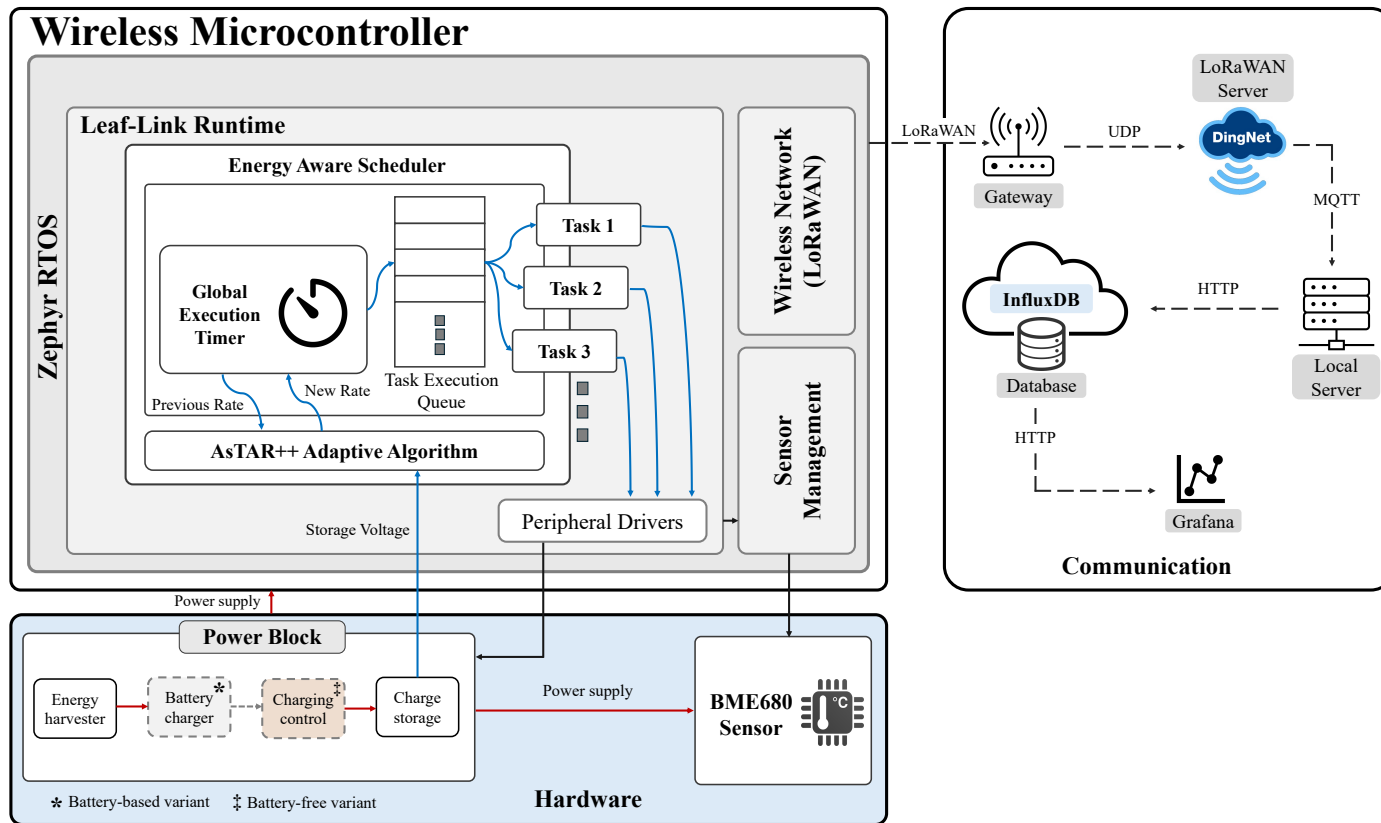


Built on FLUTE's Power Management Board

Hardware Architecture – Battery-Powered

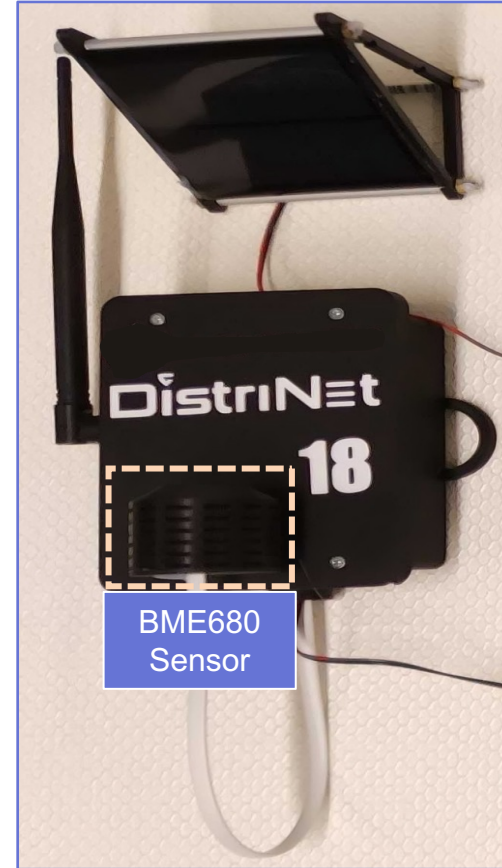
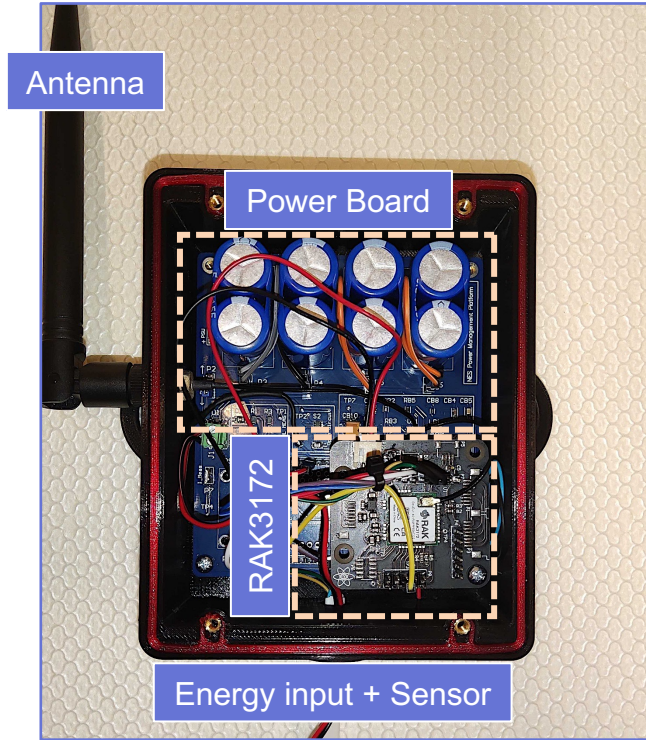


Software Architecture



Built on FLUTE's Adaptive Scheduler

Leaf-Link Reference Hardware



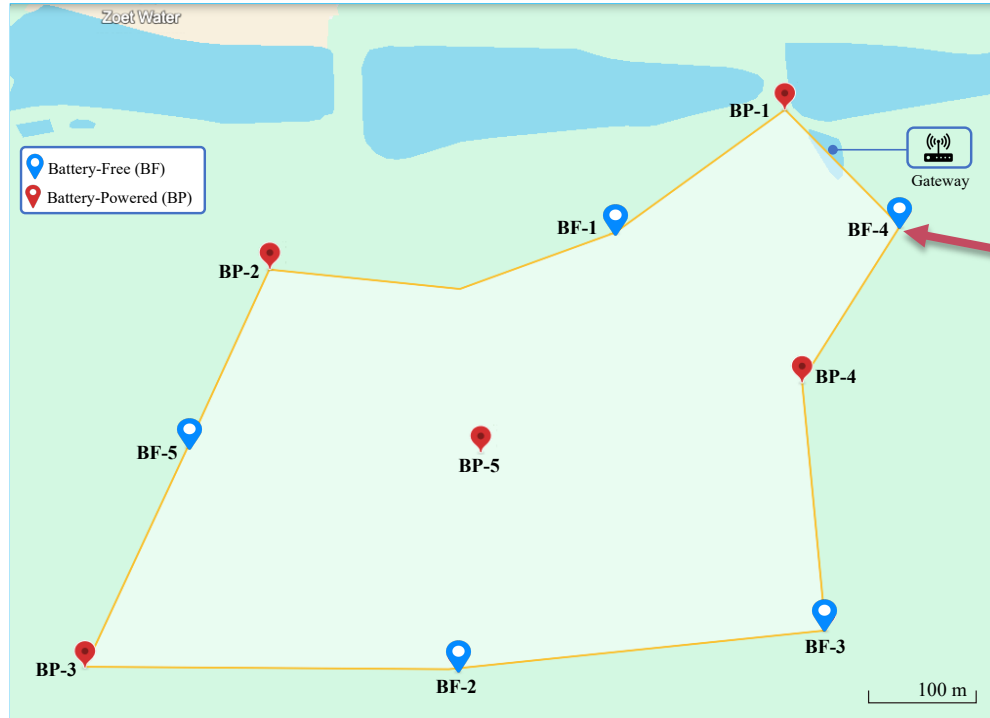
Battery-Free vs. Battery-Powered

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 V_{pv} via control switch • HV cutoff at 5.4 V	• CN3065 linear charger • Adaptive current regulation

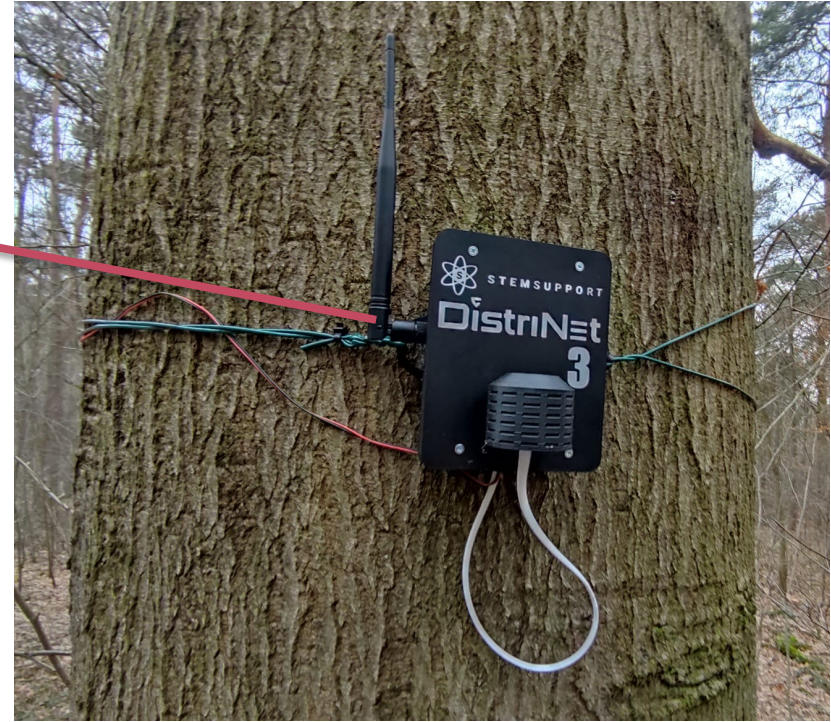
Takeaway:

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

Deployment



Nodes distribution across the forest



A representative node



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

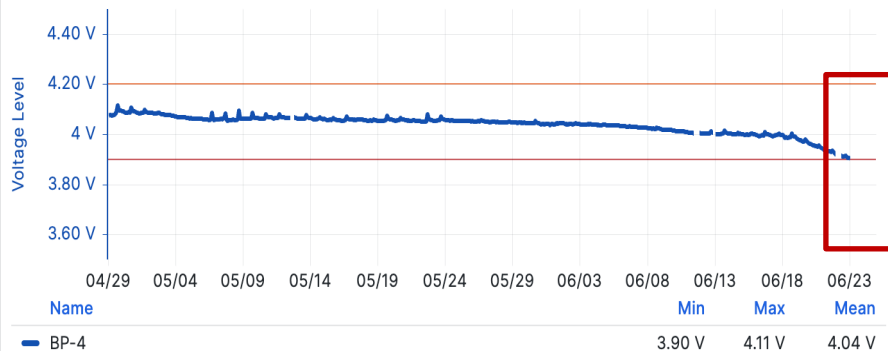
	Battery-Free (BF)	Battery-Powered (BP)
Software Failure	BF-3, BF-4	BP-1, BP-2, BP-5
Power Failure	BF-3: 16 h (then SW bug) BF-5: <9 h	BP-1: depleted after 2 weeks (no recovery) BP-4: brown-out before end
Recovery	Fast recharge (✓)	Requires ≥ 4.65 V to charge
Efficiency	Uses almost all harvested energy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

› Findings:

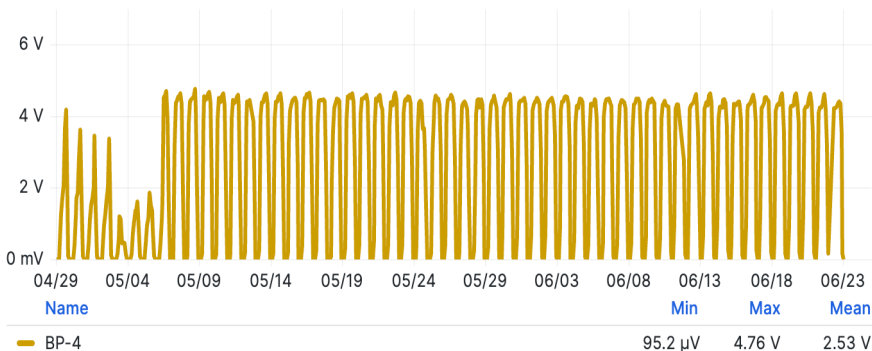
- *Most of the SW failures are linked to the **radio problems***
- *Canopy-induced reduction in solar availability results in most **power failures***

Lesson 1: Battery-free does not mean lower reliability

Battery Voltage Trace

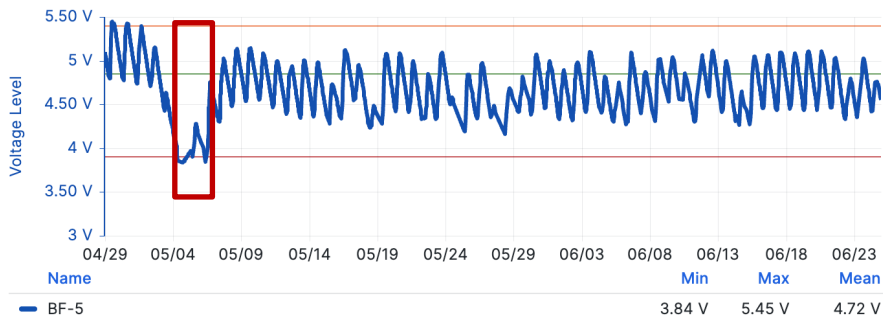


Solar Panel Voltage

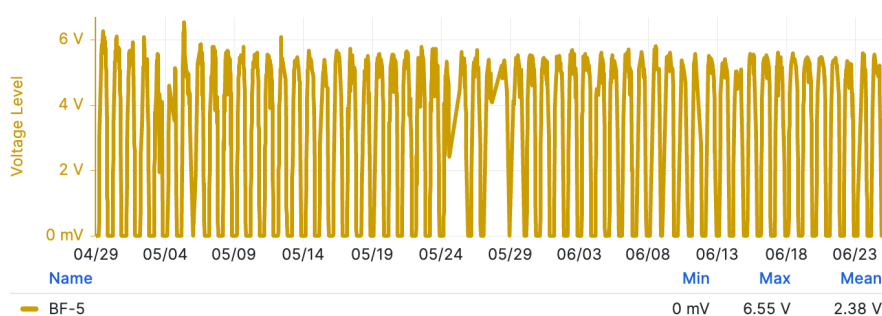


Battery-Powered Sensor Node

Supercapacitor Voltage Trace



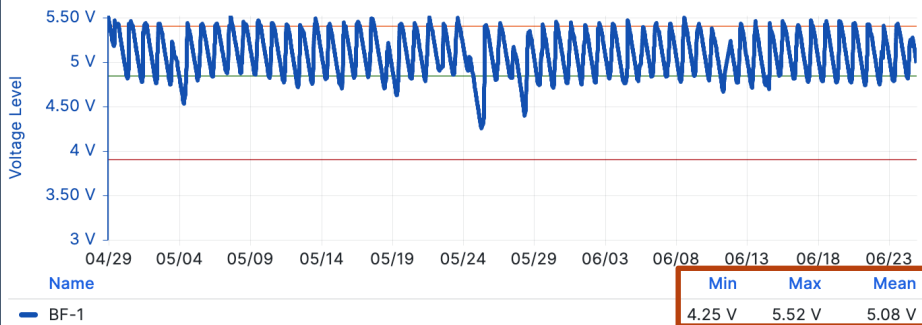
Solar Panel Voltage



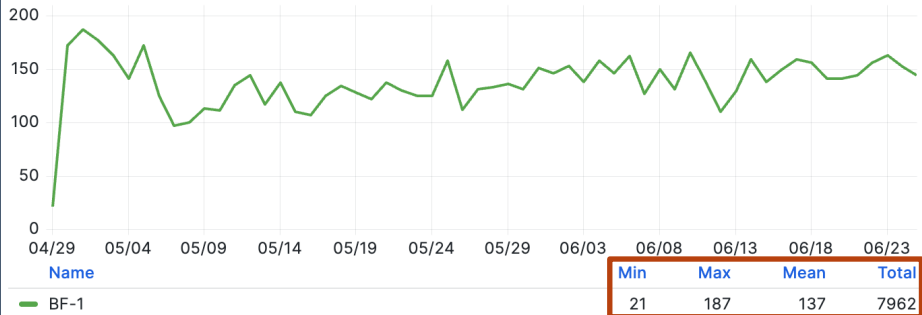
Battery-Free Sensor Node

Lesson 2: Battery-Free Devices Are Efficient

Supercapacitor Voltage Trace

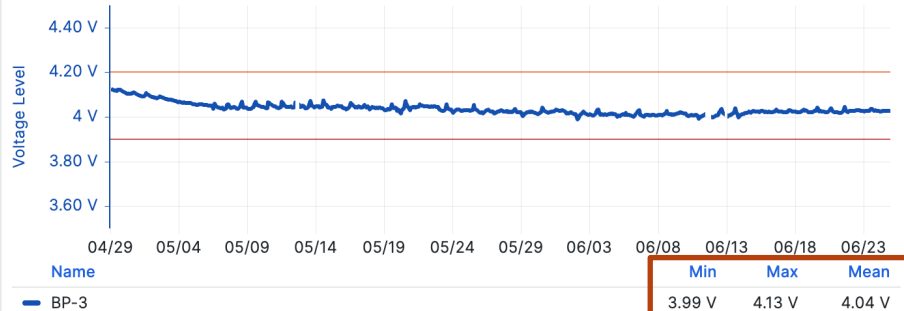


Daily Messages

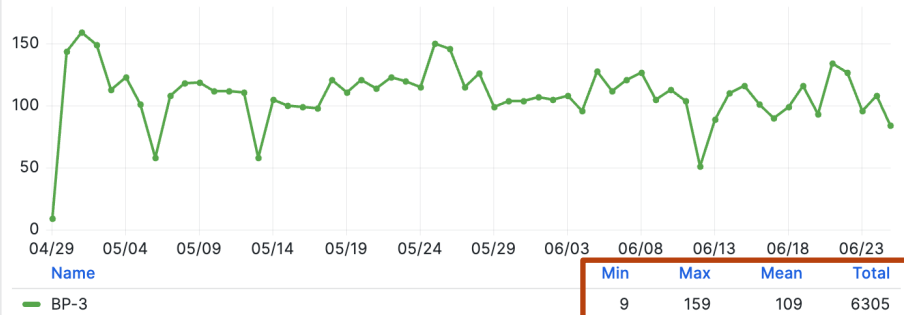


Battery-Free Sensor Node

Battery Voltage Trace

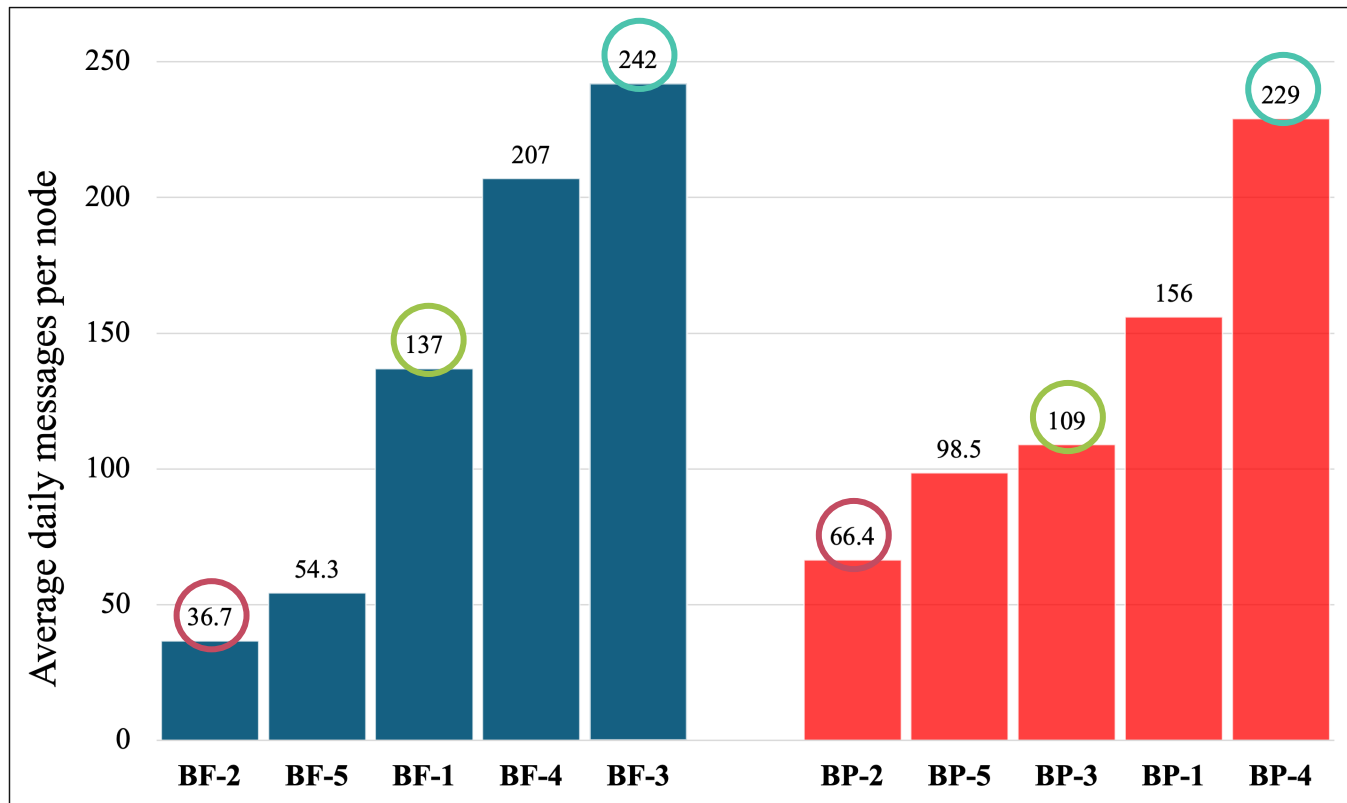


Daily Messages

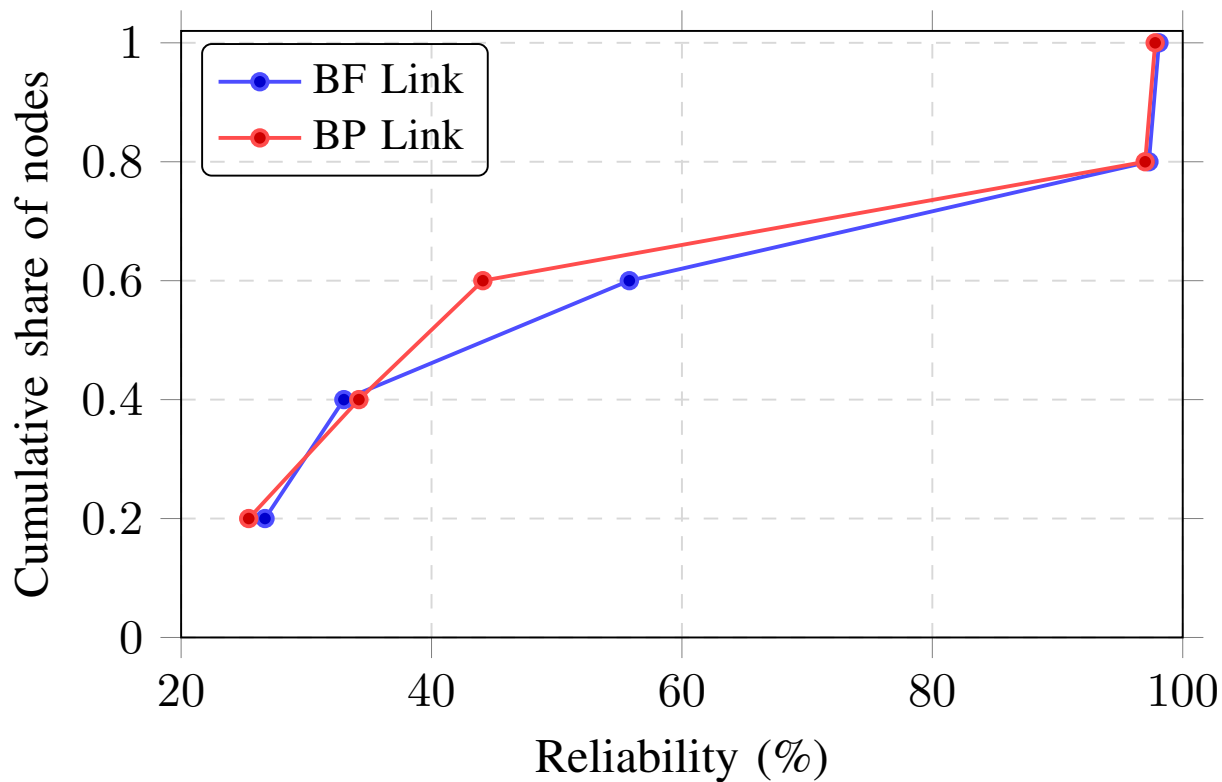


Battery-Powered Sensor Node

Lesson 2: Battery-Free Devices Are Efficient



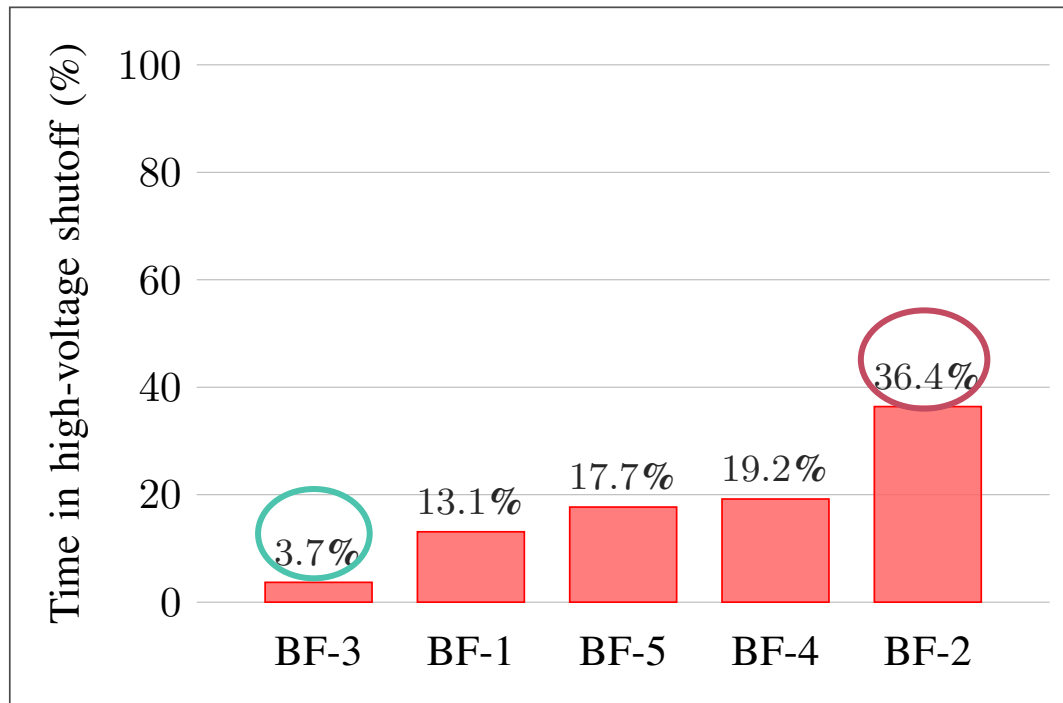
Lesson 3: LPWAN Reliability is Low in Forest Environments



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!

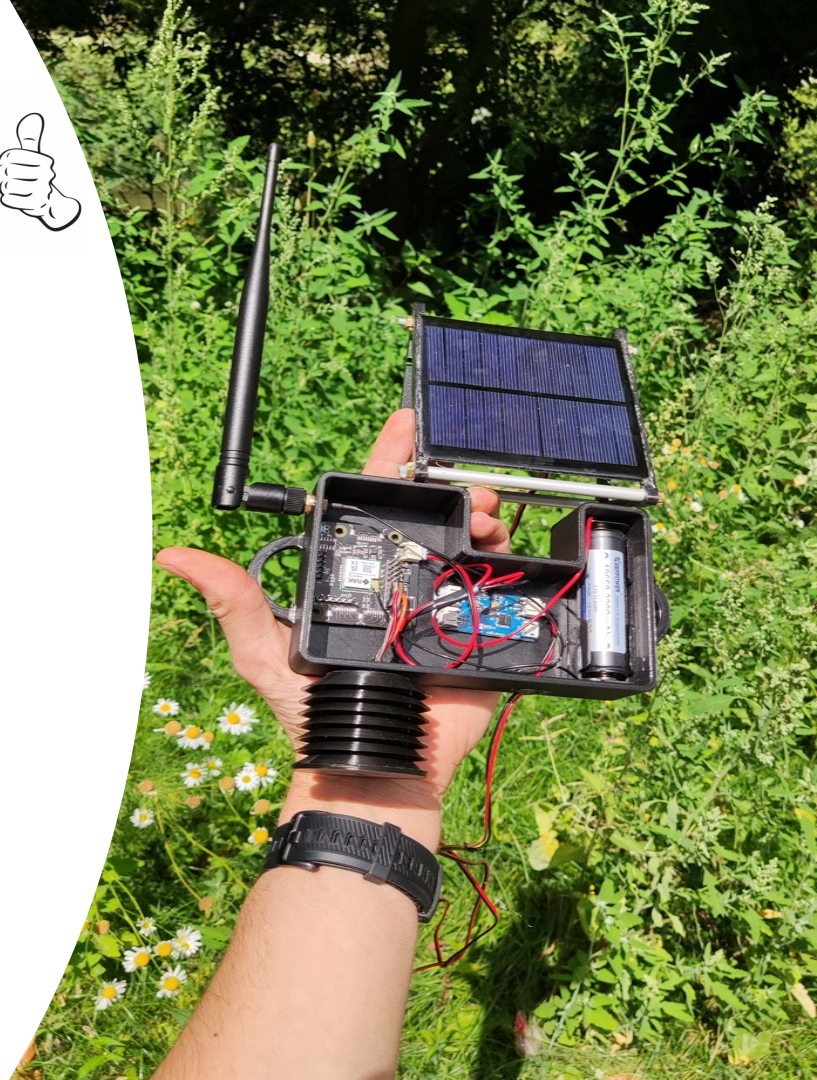


Q&A

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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 μ A
	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