Multi-Partner Project: LoLiPoP-IoT – Design and Simulation of Energy-Efficient Devices for the Internet of Things

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***Abstract*—This paper presents an overview of the Internet of Things (IoT) device design and simulation, with a specific focus on low-power design principles – everything in the context of the LoLiPoP-IoT project. The project aims to enhance IoT device usability by reducing maintenance requirements related to battery recharging or replacement. Another key goal is to significantly decrease the massive waste generated by discarded primary batteries, contributing to more sustainable and user-friendly IoT solutions for the future. The primary focus of this paper is on a custom IoT localization tag, for which we simulate solar cells – ranging from basic modeling to their integration into electrical circuits – and the power consumption of the tag's electronics platform. The analyzed sample platform is built on the nRF52833 microcontroller and the DW3110 ultra-wideband transceiver. We also applied our experimental framework principles to optimize power consumption and extend battery life. Reductions in photovoltaic panel area were achieved for both devices with a 5-year lifespan and fully autonomous tags, though with increased localization latency. Furthermore, this paper demonstrates how IoT devices, including their firmware, can be effectively modeled and simulated using publicly available tools.**

***Index Terms*—Internet of Things, Low Power, Power Autonomy, Electronic Design, Energy Harvesting, Energy Efficiency, nRF52833, DW3110, European Union Project.**

I. Introduction

Recently, the *Internet of Things* (IoT) market has experienced significant growth. The exact definition of the term IoT can vary, but the most accurate definition, however, can be found in [1], stating that IoT is "An open and comprehensive network of intelligent objects that have the capacity to auto-organize, share information, data and resources, reacting and acting in face of situations and changes in the environment." Devices connected to an IoT network are often referred to as "smart" devices. These include not only devices designed to improve our daily lives, such as smart thermostats, locks, or other sensors and actuators for home automation systems, but also industrial devices that help optimize production processes, reduce costs, and increase supply chain throughput.

A. Connecting and Powering IoT Devices

Many IoT smart devices are mobile or located in areas where access to fixed communication networks or wired electrical power is not easily available. A typical example is IoT in agriculture, with sensors spread across areas covering many square kilometers. Extending communication networks and wired power to such environments is extremely challenging and, from both a legislative and practical standpoint, often nearly impossible.

Current devices address this issue by using the *Low Power Wide Area Network* (LPWAN) technology, such as LoRa [2], Zigbee [3], or Sigfox [4]. Some network topologies also include a communication controller. In these setups, the end sensor devices are not directly connected to LPWAN but instead communicate using technologies like Wi-Fi or *Bluetooth Low Energy* (BLE) with the communication controller, which is then connected to *Wide Area Network* (WAN) using an appropriate technology.

Powering these end sensor devices, however, is more complicated. At present, commercial wireless IoT devices rely on battery power. By using suitable communication technologies, it is possible to power the device with either primary or rechargeable batteries that can last for several years currently. Nevertheless, replacing batteries in these devices is inconvenient, resource-intensive, and often highly unsustainable. For comparison, it is estimated that by 2025, 78 million batteries will be discarded due to IoT devices alone ... daily [5].

For this reason, there is an effort to replace primary batteries with other approaches, such as rechargeable batteries or supercapacitors, collectively referred to as *Energy Storages* (ES). However, providing enough energy to recharge these ES is still necessary. This is where *Energy Harvesting* (EH) technologies come into play. EH technologies allow the collection of tiny amounts of energy from the surrounding environment, typically measured in microwatts or smaller milliwatt units, depending on the technology and size of the harvester [5], [6]. Therefore, devices must avoid wasting energy and increase their power efficiency, as the amount of energy provided by EH is very limited. To approach the scale of energy that an EH can produce, we must significantly lower the power consumption of the IoT device. This increases the proportion of energy the EH can supply and extends the device's operational lifetime. Devices capable of planning their power consumption based on environmental conditions are called power-aware devices. Devices designed to minimize power consumption, often at the trade-off of some functionality loss, are low-power devices.

B. State of the Art

The following is a brief summary of literature exploring the topics of low-power and power-aware HW and SW design,

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EH, ES, and micropower management. The literature is divided into sections based on the primary focus of the achieved results. Please note that this list is written in a very concise manner, given the extensive nature of this subject:

Low-Power Hardware and Software Design: Trends in ultra-low power, ultra-low voltage, and ultra-low leakage hardware are presented in [7]. In [8], an interesting algorithm is presented, which plans the energy consumption accumulated in a supercapacitor, considering the non-ideal properties of the used supercapacitor. This technology belongs to those that have potential future use in our project. The authors of [9] demonstrate the *PERPS project*, a complex system with multisource EH. They use algorithms to predict energy availability for given node locations.

Energy Harvesting: In [6], a comprehensive overview of EH technologies is provided, including a table summarizing power densities, advantages, and disadvantages of various EH devices. This could help compare and analyze our solutions in the project. The paper in [5] presents very interesting results of the *EnABLES project*, showing, among others, the magnitude of EH technologies and their comparison. In [10], an approach is introduced involving ultra-thin solar panels that can convert any surface into an EH. Interesting ambient *Radio Frequency* (RF) EH, including efficiency comparisons for different frequency bands, is in [11].

Energy Storage: In [12], a comparison of lithium-ion batteries and supercapacitors is presented. The work in [13] demonstrates how combining lithium-polymer batteries with supercapacitors extends battery life, primarily for kinetic EH, but it is applicable to other EH devices as well.

Energy Management: In [14], a study addresses the unpredictability of EH sources and proposes a model to reduce the gap between the energy harvested and the device's energy needs. In [15], a solar energy management system using *Maximum Power Point Tracking* (MPPT) achieves 96% efficiency, optimized through simulation. Finally, [16] presents a piezoelectric EH system for car tires, featuring a new active energy balancer for supercapacitor storage. These serve as an example and comparison for the task we are working on.

C. The LoLiPoP-IoT Project

The LoLiPoP-IoT project (an acronym for "Long Life Power Platforms for Internet of Things"), under which we are making our activities, focuses on developing platforms that are low-power, power-aware, and utilize special novel HW components for micropower management and EH. The goal is to extend the operational life on a single battery (or a single recharge). The project features a total of 10 use cases, divided into three functional areas: 1) *Asset Tracking*, 2) *Condition Monitoring and Predictive Maintenance*, and 3) *Energy Efficiency and Wellbeing in Buildings*. [17]

The project has several main objectives:

1. Extend battery life by up to 5 years: Enable 400% longer battery life compared to existing commercial solutions.

2. Reduce battery waste by over 80%: Decrease batteries replaced in edge devices, reducing landfilled waste.

3. Enhance industrial and mobility asset tracking: Mitigate device loss and theft, improving efficiency and security.

4. Lower machinery downtime and maintenance costs: Use predictive maintenance to avoid unexpected failures.

5. Achieve 20%+ energy savings in buildings: Optimize district heating, increasing comfort and reducing energy usage.

6. Develop interoperable technology for diverse uses: Utilize compatible digital platforms across project use cases.

7. Promote research, standards, and knowledge sharing: Publish findings, host events, and engage in standardization and roadmap efforts.

Our university's role in the project is to contribute to a broader perspective on the energy requirements and capabilities of IoT devices, focusing on *Photovoltaic* (PV) panels as an EH source. This involves simulations of EHs and device consumption, followed by practical measurements. We also work on algorithm optimizations to minimize energy consumption, including evaluation and usage of advanced and energy-efficient *Machine Learning* (ML) techniques utilized directly on the sensor node *microcontroller* (MCU). The project overview, along with some answers to key questions, is presented in Table I.

D. Paper Outline

This paper is organized as follows. Our approach to estimating energy demand for low-power IoT devices, including experimental results, is presented in Section II. The simulation of the EH and its subsequent sizing is demonstrated in Section III, which also includes the results of our simulation experiments. Our preliminary concept of power management framework (called *DYNAMIC*) for energy-saving purposes is discussed in Section IV, alongside PV panel area reduction results. Future steps and other areas of interest are in Section V. Finally, Section VI summarizes and concludes the paper.

II. Estimating the Energy Demand

Simulation is crucial because it allows us to verify certain concepts before the actual realization and implementation of the simulated device. In the LoLiPoP-IoT project, we use three general models for three general purposes: 1) simulation and estimation of the device energy consumption during various conditions (i.e., device user settings), 2) estimation of an EH model in various environments (i.e., during a daytime, quiet period, etc.) and 3) after combining 1) and 2) with an ES model (i.e., battery, supercapacitor, or both), we are then able to estimate how powerful the EH needs to be and how often the device's battery will need to be replaced or recharged.

A. Simulation of the Device Energy Consumption

We strive to estimate the final energy consumption using simulation – the goal is to calculate the average consumption of the entire device for all its subsystems. A sufficiently accurate consumption estimation is crucial, as it directly affects the device's lifespan on a single battery.

An IoT device generally consists of multiple subsystems, each with a different consumption pattern and frequency of use, mainly depending on the firmware and settings of the IoT platform. This means that the software aspect must also be considered as an essential factor influencing power consumption. The average consumption is also a result of

TABLE I
OVERVIEW OF THE LOLIPOP-IOT PROJECT

Project Name	
LoLiPoP-IoT (Long Life Power Platforms for Internet of Things)	
Project Focus	
Low Power, Energy Harvesting, Energy Storage, Micro Power Management, Power-aware Algorithms, Power Simulations	
Project Applications	
Asset Tracking, Condition Monitoring and Predictive Maintenance, Energy Efficiency and Healthy Buildings	
Project State	Intermediate (the work reported in this paper was made exclusively by the authors of this paper)
Starting Date	2023-06-01
Ending Date	2026-05-31
Programme	HORIZON
Agency	CHIPS JU
Partners #	41
Countries Involved	Czechia, Finland, Germany, Ireland, Italy, Netherlands, Spain, Sweden, Switzerland, Turkey
Project Outlines	
Uniqueness of the Project Concept	
This project aims to reduce IoT devices' power consumption and improve the efficiency of HW and FW. We strive to enhance the usability of IoT devices in scenarios where constant maintenance is neither cost-effective nor convenient. As another significant result of our intention to enhance these power aspects, we aim to significantly reduce the enormous volumes of waste from discharged primary batteries and create more sustainable and user-friendly IoT solutions for the future.	
Usefulness of the Outcomes to the Community	
The project provides outcomes that might serve the community. These include mainly: 1) developing novel and effective EHs that go beyond state of the art, including advanced power management HW; 2) introducing innovative algorithms and frameworks for power-aware SW design; and 3) demonstrating proof of concept for devices that can significantly extend battery life.	
Solutions Expected from the Community	
We welcome suggestions and ideas for improving our systems, whether in terms of HW or SW. We are open to ideas and feedback on potential new applications and uses of low-power devices and power management algorithms. Additionally, we are seeking opinions on our framework for power-aware FW design, which we are developing, but we are still in the data collection phase through simulations.	
Project New Research Topics and Trends	
The project brings the topic of energy-efficient devices to create a more sustainable ecosystem for the IoT, as by 2025, 78 million batteries are expected to be discarded only due to IoT devices **daily** [5]. Besides all the topics mentioned previously, we also want to bring to awareness that much improvement is achievable only by using innovative SW approaches for energy planning. Last but not least, battery longevity is also about the user's convenience and cost-effectiveness. Besides these, the LoLiPoP-IoT project will also demonstrate the final effects of using advanced IoT technology in the industry, such as saving time and optimizing the throughput of industrial facilities, reducing maintenance costs that always manifest in product prices, or even enhancing building occupants' well-being, along with better energy grid planning and savings.	

the usage patterns and the environment in which the device operates.

Based on our role in the LoLiPoP-IoT project, we focus on an industrial tracking IoT tag based on the *Ultra-Wideband* (UWB) technology.

B. Specification of the Simulated Device

For demonstration purposes, we have so far modeled an industrial UWB tag, which sends a localization signal periodically every 5 minutes. This transmission period serves as a proof of concept for an initial understanding of the power consumption of the tracking tag. This concept will later be used to model the consumption of a more advanced tag, which includes power-saving measures in its algorithm to conserve energy and extend the battery life of the tag.

In order to develop the simulation model, we started by creating its energy profile. The aim is to summarize all the most important aspects of the energy consumption for the tag device. The most important parts are the MCU, UWB module, *Power-Management Integrated Circuit* (PMIC), and ES. The energy profile in Table II also includes the actual selected HW. The two last columns (in bold) are the basis for our simulation.

TABLE II
ENERGY PROFILE FOR THE TAG

Component	Note	Power Option	Value (Spec.) [1]	**Energy Value (Real) [2]**	**Period**
Energy-Consuming Components					
nRF52833 [18]	*MCU*	Active	7.29mJ/s	**7.29mJ**	**/5 mins**
		Sleep	7.8µJ/s	**7.8µJ**	**/sec**
DW3110 [19]	*UWB module*	Pre-Send	3.9165µJ	**4.476µJ**	**/5 mins**
		Send	12.382µJ	**14.151µJ**	**/5 mins**
		Sleep	0.65µJ/s	**0.743µJ**	**/sec**
Power Management Components					
TPS62840 [20]	*2xPMIC; Approx. 87.5% eff.*	Quiescent Current	0.18µJ/s	**0.36µJ**	**/sec**
Energy Storage					
Option 1: CR2032 [21]	*Primary 3V-2V*	Capacity	2117J	**2117J**	**batt. life**
Option 2: LIR2032 [22]	*Recharge-able; 4.2V-3V*	Capacity	518J	**518J**	**chg. cycle**

C. Simulation Setup and Results

The data mentioned above serve as input for our simulation. We performed the simulation using the Python3 language [23] with the help of the SimPy library [24], a process-based discrete-event simulation framework. The energy remaining in the ES during the runtime of the device is plotted in Fig. 1.

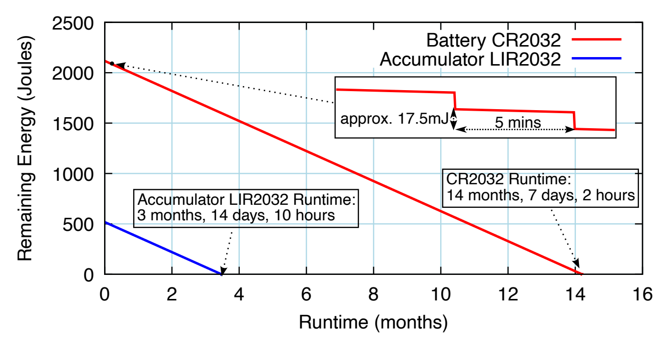

Fig. 1. Results of simulations for device energy consumption for (a) the CR2032 primary battery and (b) the LIR2032 rechargeable battery.

The figure shows that we can model the system and accurately estimate its power consumption. The presented chart is

[1]If a component is connected to multiple power rails, this value denotes the sum of energy consumed on all of them.

[2]Real energy values are calculated based on the efficiency of the PMIC (where applicable).

for a device without any EH. The rechargeable battery would last approximately 3 months, 14 days and 10 hours. In contrast, the primary battery would last 14 months, 7 days and 2 hours. This helps us estimate the final power consumption. Once the model is prepared, it can be modified to fit a different HW and configuration (e.g., changing or adding components or modifying FW settings). Our simulation models adapt freely available tools and state-of-the-art libraries. The novel aspect is easy PV panel sizing, which can improve design insights and potentially IoT energy efficiency.

III. Energy Harvester Sizing

We want to estimate the size of the EH device in advance. The goal is to verify the resulting size of the IoT device given by the EH size and confirm whether any given dimensional constraints on the IoT device are feasible. In many cases, the device must meet strict size requirements, which are often very tight. For example, our IoT device, designed to serve as an asset-tracking tag, is intended to be attached to tracked objects. In such cases, it is necessary to verify in advance whether the required dimensions are acceptable and whether the EH method meets the given conditions. Additionally, it is essential to reliably simulate the operational environment of the EH, as the environment significantly affects the amount of energy that can be harvested. An example of this is the PV panel simulation, which is our current focus.

By combining the EH model and the IoT device energy consumption model with the simulation of energy storage (battery, supercapacitor, or a combination), we aim to estimate how often the battery will need to be recharged. The goal is to merge the outputs from Section II with the outputs from this section to determine the necessary sizing of the EH to achieve the desired lifespan on a single charge.

A. Light Conditions for PV Simulation

Information about the operational environment is necessary to simulate the PV panel in that specific environment accurately. The most important factor is light intensity, although some PV panels are also sensitive to ambient temperature. As we focus primarily on indoor use, the light intensity is the most important. Since we do not yet have precise measurements of the usage environment, we base our simulation on carefully selected data derived from available sources.

First, we specify the light intensity in lux (lx) for different environments where the localization tag may operate:

Sun: For reference purposes; powerful illumination on a clear day when sunlight directly hits the panel: 107 527 lx = 15.7433382 mW/cm^2,

Bright: Stronger ambient lighting when the tag is handled in areas designated for manual work: 750 lx = 109.8097 µW/cm^2,

Ambient: Lower ambient lighting when the tag is placed in a less illuminated area intended for quiet work or rest (e.g., at home): 150 lx = 21.9619 µW/cm^2,

Twilight: Very dim environment when the tag is placed in a semi-open cabinet or similar (comparable to light levels before sunrise or after sunset – hence the denotation twilight): 10.8 lx = 1.5813 µW/cm^2.

All the light level data in the overview above were taken from [25] and converted to W/cm^2, which is the unit used by our simulation tool PC1D [26]. An overview of these environments, including the duration of time spent in each environment, can be seen in Fig. 2.

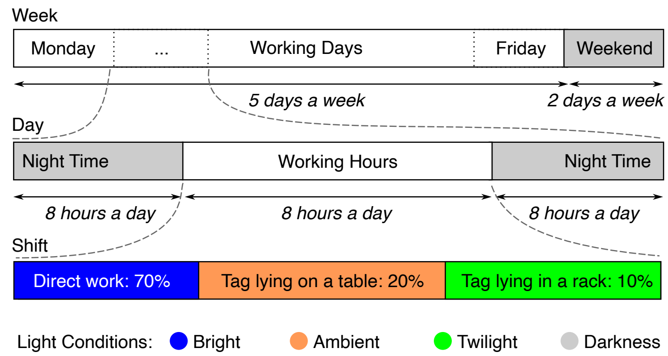

Fig. 2. Scenarios of the tag usage in our simulated environment; please note that the colors and lighting conditions names are consistent to the previous list and the chart in Fig. 3.

B. PV Cell Simulation

In our case study, we utilize PC1D [26], a simulation software specifically designed for modeling the electrical and optical properties of PV cells. This tool allows us to simulate PV cells at a physical level, offering insights into the performance and behavior of panels, even when detailed datasheets are unavailable or insufficient for our purposes. Using the PC1D, we can estimate various important parameters, such as *current- and power-voltage* (I-P-V) characteristics. The software's ability to simulate these low-level properties makes it also an ideal tool for modeling experimental and custom-made PV cells.

To create an accurate model in PC1D, we first input key material and device parameters specific to a crystalline silicon (c-Si) solar cell, which we use in our simulations. These parameters include material properties such as doping concentration, device geometry, and the thickness of individual layers. For instance, in our model, we used a 200 µm thick region of N-type silicon, doped with P-type material, and assumed 2% front reflectance without surface texturing. By simulating various conditions, the PC1D provides us with insights into the internal workings of the PV cell.

The results of the PC1D simulation include a range of outputs, with the I-P-V curve being one of the most crucial for assessing the cell's overall performance. The I-P-V curve provides important information about the panel's potential power output. The results of our simulation can be observed in Fig. 3. Please note that we simulate a solar panel with a size of 1cm^2. We chose this size so that the output of larger panels can be multiplied according to their area and thus approximated. However, the voltage will, of course, remain the same in a parallel configuration.

As can be observed from the chart, light intensity significantly impacts the maximum achievable voltage and current and, thus, of course, the *Maximum Power Point* (MPP). As is evident, the cell's power output in direct sunlight (*Sun* result) is by far the highest, approximately two to three orders of

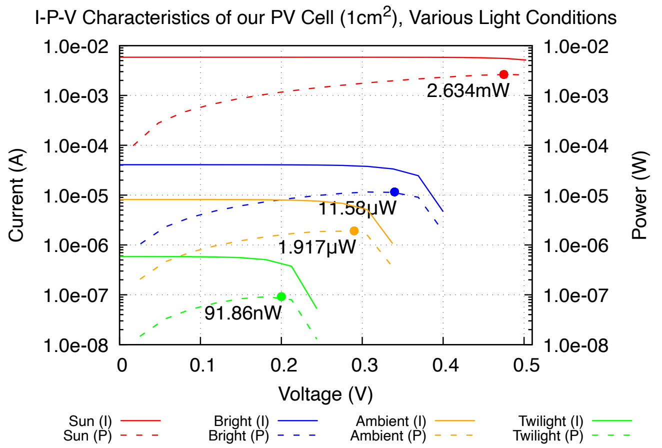

Fig. 3. Results of simulations for our c-Si PV panel, 1cm^2, under various light conditions; the maximum power points are denoted by a colored dot in the chart.

magnitude greater than the power output under artificial indoor lighting (*Bright* and *Ambient* results). These two environments, in turn, provide roughly two orders of magnitude higher power than the weakest environment (*Twilight* result). Therefore, the device's exposure to the *Bright* and *Ambient* environments brings the most energy. The tag will rarely be exposed to direct sunlight; therefore, the *Sun* environment should be considered for reference purposes only.

C. PV Panel Sizing

Next, we need to determine how large a panel would be required for the device to operate in the described environment while being a) completely autonomous and b) achieving a battery life of at least five years. For this purpose, we prepared a simulation model that includes the device model already presented earlier in this paper and the experimental PV panel made of cells, which were also simulated earlier in this publication. The device model itself will 1) use only a rechargeable battery and 2) be extended with a battery charger in the form of a chip – in our case, the BQ25570 [27], with an efficiency of 75% in our specific use case and a quiescent current of 488nA (i.e., 1.7568µJ/s at 3.6V).

This simulation is also run using Python3 language [23] with the help of the SimPy library [24]. The results of several selected simulation runs can be seen in Fig. 4. As observed, panels with an area of up to 36cm^2 (incl.) do not meet the requirement for an operational period longer than five years, although the 36cm^2 panel comes close with a lifespan of four years and nine months. The device using a PV panel with an area of 37cm^2 has a lifespan of nearly nine years, and the device with a 38cm^2 panel almost achieves complete power autonomy, as the battery would degrade and the electronics would become outdated before the power runs out.

The chart also shows that as we increase the PV panel area and approach energy autonomy, a much smaller increase in panel area is needed to make a significant improvement. For example, the first four plot lines increase by a step of 5cm^2, but for the subsequent plot lines, the step is only 1cm^2. Yet, the runtime is rising even more.

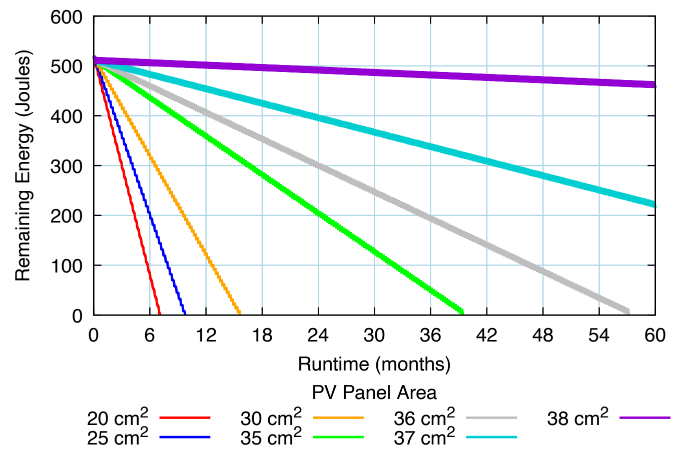

Fig. 4. Results of simulations to show the remaining energy in the LIR2032 accumulator for various sizes of the PV panel.

Please note the oscillating lines on the plot, caused by weekends during which our simulated building is not operating, rendering the tracker out of light and, thus, out of energy. This was identified during the simulation results analysis as the main factor significantly reducing the lifespan on a single charge. The issue is that the device consumes so much energy over the weekend that during the following working days, there is not enough opportunity to not only power the device from the PV panel but also make up for the weekend power shortfall. This issue did not arise with nighttime power outages, as the night is much shorter than the two-day weekend.

IV. Dynamic Power Management

As evident, the PV panel that meets the requirement for a) a five-year lifespan or b) fully autonomous operation is too large. It can, therefore, be assumed that achieving extended battery life on a single charge will require incorporating innovative software mechanisms for energy saving. For instance, it may not be necessary to send location data as frequently if the device is aware that the energy supplied from the EH is insufficient. On the contrary, if the energy supply is sufficient, localization can be more frequent again.

As part of the LoLiPoP-IoT project, we are also working on a unique framework called the *Dynamic Management Interface for Power Consumption* (DYNAMIC), the basic concept of which we have already published in [28]. Currently, we are focusing on C++, but the idea is also fundamentally transferable to other languages. This framework aims to 1) simplify and unify the process of transforming firmware that does not consider power consumption into power-aware implementations, which in turn leads to broader adoption of power-aware IoT devices and indirectly helps reduce battery waste coming from them, and 2) separate the firmware logic from power management logic, making algorithms more portable and more accessible to adapt to other devices.

The DYNAMIC framework has so far been simulated with two algorithms designed explicitly for DYNAMIC. One (i.e., the "Slope" algorithm earlier presented in [28]) will be demonstrated to optimize the energy consumption of our IoT tag's firmware. The optimization lies in the algorithm automatically selecting the localization signal period based on the energy received from the EH. The chosen algorithm, called "Slope," is based on monitoring the battery's charge progress. Suppose it detects the battery's charge slope trending downward at a certain angle (in our experiment, -0.0001 $\times$ panel area in cm^2). In that case, it increases the period by a predefined value (for us, 15 seconds), and vice versa for increasing the period when the slope is positive (with a threshold of +0.0001 $\times$ panel area in cm^2). The maximum time for sending signals is set to one hour, and the minimum is five minutes (the default value). The algorithm can also utilize energy that is beyond the battery's capacity (in our case, the algorithm would reduce the period below the default). However, this feature is not utilized here. The results of the simulation for a device with this firmware adjustment in the same environment, as described above, can be seen in Table III.

TABLE III
BATTERY LIFE AND LATENCY WHEN USING SLOPE ALG.

PV Area [cm^2]	Slope Alg. Settings (deg.)	Battery Life	Added Latency [seconds] Work	Night	Focus
5	±0.25e-3	2 Y, 127 D	3180	3300	work latency
6	±0.3e-0	3 Y, 9 D	3180	3300	
7	±0.35e-3	4 Y, 86 D	3180	3300	
8	±0.40e-3	7 Y, 27 D	3165	3300	
9	±0.45e-3	21 Y, 189 D	3165	3300	
10	±0.50e-3	∞	3210	3300	energ. autonomy
15	±0.75e-3	∞	3195	3300	
20	±1.0e-3	∞	1740	1860	night latency
25	±1.25e-3	∞	690	1020	
30	±1.5e-3	∞	480	645	

As can be observed, our preliminary results indicate that, at the cost of increased localization latency, it is possible to reduce the PV panel size by up to 77% (from 36 to 8cm^2) for devices exceeding a 5-year lifespan and by 73% (from 38 to 10cm^2) for devices targeting fully autonomous operation without the need for recharging. The increased latency ranges from 3165 to 3300 minutes for devices aiming for a 5-year lifespan and from 480 to 645 minutes for those targeting full autonomy (for the latter, of course, after a larger PV panel of 30cm^2 is used). In both cases, the highest latency increase is consistently observed during weekends when the simulated environment represents an empty building, i.e., the device is in complete darkness. Please note that these results are experimental, and the DYNAMIC framework was only simulated in these cases.

V. FUTURE STEPS AND OTHER AREAS OF INTEREST

The paper presented an extensive approach to simulating PV EH. In our future work, we plan to collaborate with our partners to collect accurate lighting data from the locations where the localization tags will operate and further refine the simulation according to the specific environment. Although we have striven for maximum accuracy and modeled the system with high fidelity, we aim to measure the actual energy consumption in a real UWB localization application in the future. For this purpose, we plan to use the same hardware as described in the article and conduct real-world measurements.

Another area our team is working on is minimizing energy consumption by enabling IoT devices to preprocess data directly within the MCU. Our hypothesis is that the transmitter consumes a significant amount of energy, and by reducing the amount of transmitted data through preprocessing, we can significantly reduce energy consumption. However, it is also necessary to consider the MCU's energy consumption. Therefore, in our previous publication [29], we focused on evaluating the energy efficiency of different machine learning frameworks specifically for MCUs.

The final area we are also exploring in this project is the use of machine learning capabilities running on MCUs for predictive maintenance, i.e., planning maintenance for industrial equipment with a focus on low-power IoT sensors. Again, the goal is to minimize costs, reduce environmental impact, and maximize the throughput of industrial systems.

VI. CONCLUSIONS

This paper introduces IoT devices and the basics of their low-power design. The introduction also describes the European project of which our work is a part. The paper then focuses on the simulation of solar cells, from the lowest level up to their integration into electrical circuits. The paper also includes a simulation of the power consumption of the IoT localization tag we designed based on the nRF52833 platform in conjunction with the UWB controller DW3110. Our framework, called DYNAMIC, which is still in the experimental stage, has also been incorporated and evaluated. The framework aims to adapt the device's power consumption to maximize the battery life. We emphasize our motivation, which is significant economic savings from reducing battery consumption and minimizing the service interventions needed for battery replacement or recharging. Last but not least, the goal is to reduce the environmental impact, which, according to [5], will reach 78 million batteries per day by 2025.

The results show that by using freely available tools, it is possible to simulate IoT devices, including simple firmware. In our findings, we achieved a PV panel area reduction of 77% and 73% for devices with a 5-year lifespan and fully autonomous devices, respectively. However, this comes at the cost of increasing localization latency by 3300 seconds in the worst cases. We plan to improve the algorithm further and are considering new ways to reduce the tag's power consumption, such as incorporating additional sensors (e.g., an accelerometer) and utilizing the newly acquired data for context-aware power management planning.

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