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FELIPE AUGUSTO VITORIANO

Assessment of an adaptable data diet for a self-powered wireless IoT sensor system

BELO HORIZONTE, BRAZIL
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FOLHA DE APROVAÇÃO

"Assessment Of An Adaptable Data Diet For A Self-powered Wireless Iot Sensor System"

FELIPE AUGUSTO VITORIANO

Dissertação de Mestrado defendida e aprovada, no dia 26 de abril de 2022, pela Banca Examinadora designada pelo Colegiado do Programa de Pós-Graduação em Engenharia Elétrica da Universidade Federal de Minas Gerais constituída pelos seguintes professores:

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Belo Horizonte, 26 de abril de 2022.

To my family and friends

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“Te Deum laudamus: te Dominum confitemur...”

(Saint Ambrose, 5th century)

Abstract

VITORIANO, Felipe Augusto. **Assessment of an adaptable data diet for a self-powered wireless IoT sensor system** 2022. 56 p. Dissertation (Master of Science) – Graduate Program in Electrical Engineering, School of Engineering, Universidade Federal de Minas Gerais, Belo Horizonte, 2022.

The advance of Internet of Things (IoT) technologies in the last decades have been enabling a myriad of applications in houses, hospitals, industries, farms and even on and in our bodies. Spreading these technologies also means facing increasingly complex engineering challenges. This project describes a modular design of a low-power proof-of-concept IoT module with wireless communication, light sensing, as well as energy harvesting, storage, monitoring and management capabilities. This system has been developed aiming at assessing a self-adaptable approach to balance energy consumption and generation, in view of a lifetime-long independently node. Results from validations are shown pointing out bottlenecks and possibilities for improvements, considering the constraints in size, energy and communication of IoT technologies.

Keywords: energy harvesting, internet of things, low power, autonomous sensors.

Resumo

VITORIANO, Felipe Augusto. **Avaliação de uma dieta de dados adaptável para um sistema de sensores IoT sem fio autoalimentados**. 2022. 56 f. Dissertação (Mestrado em Microeletrônica e Microssistemas) – Programa de Pós-Graduação em Engenharia Elétrica, Universidade Federal de Minas Gerais, Belo Horizonte, 2022.

O avanço das tecnologias de Internet das Coisas (do inglês Internet of Things, ou IoT) nas últimas décadas tem possibilitado uma infinidade de aplicações em residências, hospitais, indústrias, agronegócio e até mesmo no corpo humano. Difundir estas tecnologias também significa enfrentar desafios de engenharia cada vez mais complexos. Este projeto descreve o desenvolvimento de uma prova de conceito de um módulo IoT de baixa potência com comunicação sem fio, sensor de luz, bem como recursos de coleta, armazenamento, monitoramento e gerenciamento de energia. O sistema foi desenvolvido com a intenção de se avaliar uma abordagem auto-adaptável para equilibrar o consumo e a geração de energia, visando um nó capaz de operar de forma independente ao longo de sua vida. Os resultados das validações são mostrados neste trabalho apontando gargalos e possibilidades de melhorias, considerando as restrições de tamanho, energia e comunicação das tecnologias IoT.

Palavras-chaves: colheita de energia, internet das coisas, baixa potência, sensores autônomos.

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List of abbreviations and acronyms

IoT	Internet of Things
MCU	MicroController Unit
IC	Integrated Circuits
MEMS	MicroElectroMechanical Systems
I2C	Inter-Integrated Circuit Protocol
WSN	Wireless Sensors Networks
LDO	Low-Dropout Linear Regulators
BLE	Bluetooth Low Enery
LoRA	Long Range Wide Area Network
PoC	Proof-of-Concept
PV	PhotoVoltaic
API	Application Programming Interface
REST	Representational State Transfer
JSON	JavaScript Object Notation
AWS	Amazon Web Services
CSV	Comma-Separated Values

List of symbols

Δ	Greek letter Delta (Uppercase)

Contents

1 Introduction

1.1 Motivation

The exponential advances in data and mobile devices, cloud-based systems, semiconductors, Integrated Circuits (IC), Microelectromechanical Systems (MEMS), sensors and wireless technologies have been enabling a myriad of technology applications in houses, hospitals, industries, farms and even on and in our bodies. The development of Internet-of-Things (IoT) devices has been showing a substantial growth (CAPRA *et al.*, 2019), with over 100 billion devices to be deployed by the year 2050, as expected by Gartner (GARTNER, 2021), who also indicates that the path towards a digital future is accelerating due to the COVID-19 pandemic.

Spreading these technologies also means facing increasingly complex challenges. Some examples of what has been done in order to allow the consistent growth of such technologies in the following years are powering distributed devices, the use of batteries capable of feeding devices for their lifetime, harvesting energy from the environment, managing power, connecting and communication in long range, dealing with network latency, managing and processing data.

The "hyperautomation", distributed monitoring and digitalization of processes are inevitable, and IoT devices started to play a prominent role in these perspectives some years ago. Figure 1 shows the trends on the rapidly increasing use of digitalization techonologies.

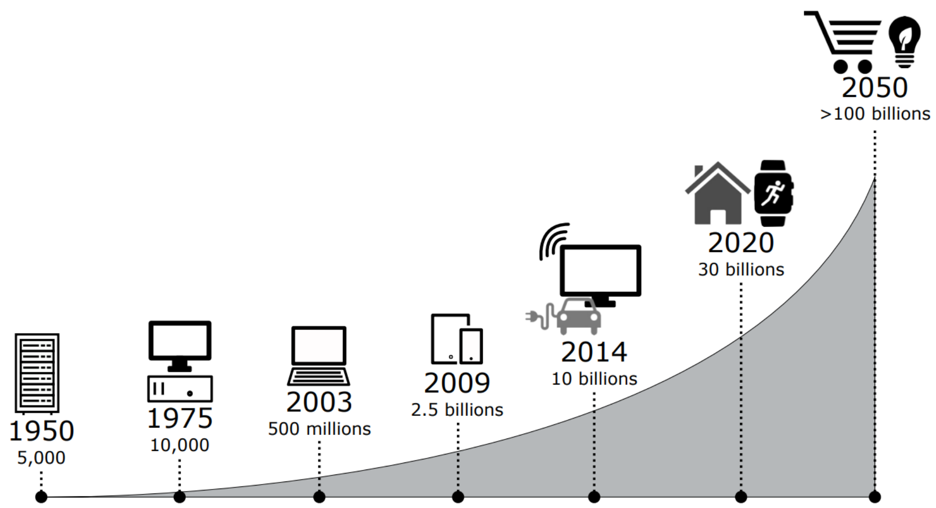

Figure 1 – The rapidly increasing adoption of digitalization technologies[1].

Dense wireless networks of heterogeneous sensing nodes, which collect and transmit a wide range of environmental data, enable a multiplicity of exciting, safer and even more efficient scenarios (AMMER *et al.*, 2005). To mention just a few: smart homes with optimized ambient control, energy management, integrated security and person identification; robot guidance in manufacturing environments, predictive maintenance and warehouse inventory in industries; integrated patient monitoring, diagnostics and drug administration in hospitals; smart shopping centers; interactive toys and museums; smart farms and an immeasurable amount of current and future applications to come.

1.2 Ambient Intelligence

Considering the close interaction between devices and infrastructure in these scenarios, Weber *et al.* proposed the label "ambient intelligence" should be attributed to such environments (WERNER; RABAEY; AARTS, 2005).

From the history point of view, talking back to the previous "waves of computing" which sailed in the last decades resulting especially from the continuation of Moore's law, one can see that the first wave came with the introduction of mainframe computing, with a "many people to one machine" model. The second wave is related to the one-to-one relationships between people and their so called personal computers - the "one person to one machine" approach. Then, the third wave takes a move from this model of people accessing internet computing services almost exclusively via a personal desktop computer to a "many people to many machines" model (MANWARING; CLARKE, 2015). This third wave is then now commonly called pervasive computing and/or ambient intelligence (AMMER *et al.*, 2005).

Figure 2 elucidates the three waves of computing, culminating in the evident third one, the complex interconnection of people and machines. As (SNIJDERS, 2005) says,

> The concept of Ambient Intelligence requires major technological advances in sensor and microactuator technology, in ultra-low power radio and in smart materials to create the adaptiveness and responsiveness of the Ambient Intelligence environment. Furthermore, massive research and progress in energy scavenging from the environment to power autonomous, unattended micro systems and in the self-organization aspects of those Ambient Intelligence devices is needed. Last but not least, all technology elements have to be integrated into the architectural framework of an Ambient Intelligence System with which the user interacts at the application level in a multi-modal way. These technologies will form

[1] source Adapted from (CAPRA *et al.*, 2019)

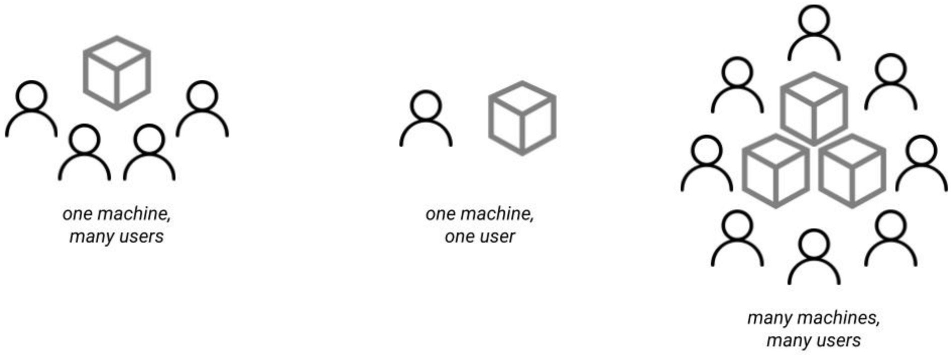

Figure 2 – The three waves of computing

a "library" of building blocks for general ambient intelligence system architectures.

The intelligent approach now brought to environments, and the many-persons-to-many-machines perspectives are, therefore, a complex and multi-layer challenge in which IoT devices play a prominent role. The technical, energetic, infrastructural, security, economical, cultural and social aspects must be taken into account in order to allow the viability of these increasing developments.

1.3 Self-powered devices

From the engineering perspective, the widespread deployment of IoT technologies are constrained by three main important metrics: cost, size and power. However, of the three implementation restraints, power (or energy, depending on how the node is powered) turns out to be crucial for stand-alone devices (AMMER *et al.*, 2005).

New Wireless Sensor Networks (WSNs) have been driven towards IoT devices that are self-sufficient from an energy perspective, preferably throughout their full lifetime. Such nodes should then, in a technical convenient way, be able to harvest energy from the ambient to meet its survival demands, being then able to collect, process and transmit data to its data-receiving peer.

Therefore, energy harvesting, storage and charge management capabilities are essential to self-powered nodes. The autonomy of a node, however, closely relies on how much power it is able to generate, given the environmental conditions, and how power eager it is. Nodes must accordingly adapt its data and operation diet to the amount of available energy. This means, in other words, that it should be able to adjust how much data is collected and the intermittence of their transmission.

Corke and others (PETER *et al.*, 2007) present some already developed works on devices with the ability to vary its duty cycle based on available energy. An interesting case is brought up by Jiang *et al.* (JIANG; POLASTRE; CULLER, 2005), who presents some basics on perpetual environmentally powered sensor networks, showing the development of a prototype with a sensor node relying on solar energy, super-capacitor and Li-ion batteries, using a Telos-mote module (POLASTRE; SZEWCZYK; CULLER, 2005). A more recent review by Adila *et al.* (SYEDA; ALMUSAWI; GéZA, 2018) also discusses trends on the currently named "green" IoT, with a brief overview of harvesting technologies aimed to power up IoT nodes. Other additional works can be found in the literature as the one from (KJELLBY *et al.*, 2018), who built a proof-of-concept system for a maintenance free, completely self-sustainable and self-powered node, using a very similar perspective to the one that was used in this project.

In light of these considerations, this project corresponds to a system wide development, assessment and validation of a proof-of-concept IoT module, with wireless communication, sensing and energy harvesting capabilities. A self-adaptable power approach for balancing energy consumption and generation was also developed. In view of the obtained results, one can point out some bottlenecks and possibilities for improvements, considering the constraints in size, energy and communication of IoT technologies.

1.4 Goals

1.4.1 General Goals

The purpose of this work is to systematically design, develop and validate a proof-of-concept IoT device with energy harvesting, sensing and communication capabilites, having in mind the power constraints of an autonomous device.

1.4.2 Specific Goals

The specific goals of this work are stated below:

- Develop a system-level architecture for a self-powered device
- Specify the suitable parts for each internal module, in order to build a functional prototype for validations
- Conceive an energy harvesting module
- Conceive an energy storage and management module
- Conceive a sensor module
- Conceive a micro-controller module
- Conceive a communication layer and a remote server module
- Mathematically characterize the energy consumption and generation profiles
- Build a device with such characteristics and modules
- Perform tests in real case conditions
- Compare the practical results with the theoretical ones
- Evaluate the obtained results and propose next steps

2 Technical Background

This chapter presents the basis for building the device here documented, including theoretical concepts and hardware modules specifications as following.

2.1 Micro-controller Units (MCU)

A micro-controller is a compact integrated circuit designed to perform a specific task in an embedded system. It is a key element in an IoT node, in which it is responsible for orchestrating the operation of sensing transducers, performing calculations and logical operations, communicating and transmitting data. Typical micro-controller units usually incorporate a processor, memory and input/output modules to connect to peripherals.

2.1.1 ESP32

One of the most widely spread used MCUs for IoT applications is the the ESP32 (SYSTEMS, 2021) from Espressif Systems, a multinational Chinese company. The ESP32 is a low-cost low-power system-on-a-chip microcontroller with integrated communication peripherals. ESP32 is highly integrated with built-in antenna switches, RF balun, power amplifier, low-noise receiver amplifier, filters, and power management modules. It allows sleep modes and a variety of wake-up triggers, being suitable for low-power applications.

It has an Xtensa® Dual-Core 32-bit LX6 processor, and supports Bluetooth Low Energy (BLE) and WiFi 802.11 b/g/n 2.4 GHz - 2.5 GHz interfaces. This MCU, besides its main core, has also a RTC (real-time clock) and a ULP (Ultra Low Power) co-processor. In this project, an off-the-shelf ESP32 Wemos WROOM-32 module with built-in voltage regulation components was used (see Figure 3). Besides having the advantage of including regulation circuitry, this module was chosen due to its availability and deployment in other currently related projects that may adopt the learned lessons from this work.

Although other modules should be more efficient, this project is focused on the system-oriented design rather than on the module-oriented design, aiming at delivering an analysis of energy balance. This study, however, can later be applicable to other combinations of different modules.

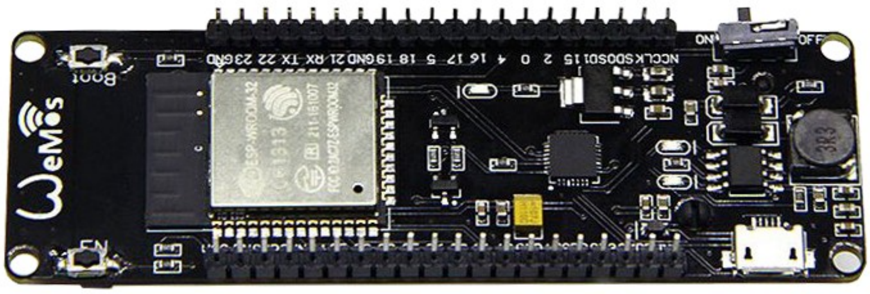

Figure 3 – ESP32 Wemos WROOM-32 module

Mode	Radio	Core	ULP[*1] Processor	RTC[*2]	Current
Active	active	active	active	active	160-260 mA
Modem Sleep	inactive	active	active	active	20-68 mA
Light Sleep	inactive	active, can be paused	active	active	0.8 mA
Deep Sleep	inactive	inactive	active	active	10-150 uA
Hibernation	inactive	inactive	inactive	active	5 uA

Tabela 1 – ESP32 operation modes

Source: Compiled from Espressif Systems (SYSTEMS, 2021)

[*1] ULP: Ultra Low Power

[*2] RTC: Real Time Clock

2.1.2 Sleep modes

Within the scope of low power devices, one should generally appeal to the use of sleep modes, a strategy for saving energy by deactivating some MCU resources when they are not required.

ESP32 has advanced power management features, and offers five configurable power modes, with different power saving capabilities: Active Mode, Modem Sleep Mode, Light Sleep Mode, Deep Sleep Mode, and Hibernation Mode. These mechanisms are compared in Table 1, showing which sub-part of the chip is kept active or not in each mode.

In deep-sleep mode, one of the leanest ones, the CPU, most of the RAM and all the communication and digital peripherals are powered off. The ULP processor, RTC controller, its peripherals and memories are the only resources which remain active when in deep-sleep mode. The wake-up timer can be used to activate the full ESP module periodically to run the active mode and perform a task (measure and transmit data, for example). As seen before, the chip consumes tens of micro amperes when in deep sleep.

2.1.3 Inter-Integrated Circuit Protocol (I2C)

Inter-Integrated Circuit, abbreviated as I2C, is a serial bus protocol developed by Philips Semiconductor. It is suitable for short distance communication between multiple peripheral chips (such as sensors and MEMS) and one or more controller(s). ESP32 has a built-in I2C interface, which was used in this project for interfacing with two sensors, as detailed in the next section.

2.2 Sensors

Sensors are mainly used as input data source for IoT devices. The variety of sensors allows the measurement of specific quantities from the environment, converting the value of interest into a digital/analog signal that can be read by a MCU. The following subsections present two reading modules incorporated to the referred prototype device.

2.2.1 BH1750

BH1750 (ROHM, 2021) is a digital 16-bit ambient light sensor IC from Rohm Semiconductor, equipped with an illuminance-to-digital converter featuring wide range (1 to 65535 lux), with an I2C bus. It was used as light sensor in this project. Figure 4 illustrates a BH1750 commercial module.

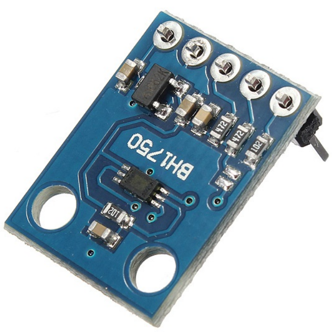

Figure 4 – BH1750 commercial module

2.2.2 INA219

The INA219 (TEXAS, 2021) is a complete current shunt and power monitor with an I2C interface. The device monitors instant voltage, current and power in the circuit attached to it. This IC was used as a power meter for a photovoltaic cell, as will be shown later. Figure 4 presents a commercial module featuring INA219.

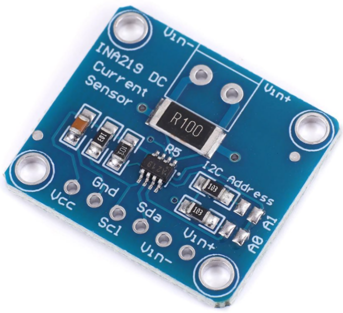

Figure 5 – INA219 commercial module

2.3 Power restrictions

In the majority of WSNs and IoT applications, most or even all devices must be un-tethered and work independently of external connections. This keeps costs down and allows flexible deployments. It is usually met by using wireless communication and battery powered systems. However, power is known to be the main challenge in these scenarios, since wireless data transfer poses dense energy demands and batteries have limited life time - ranging from hours to months, and rarely to years.

When batteries are depleted, they need to be replaced or recharged. For devices in remote locations and harsh environments, or deployed in large numbers in a network, it may not be possible to do either (THAKUR; PRASAD; VERMA, 2017). Energy harvesting from ambient sources is a viable solution to overcome these issues (KJELLBY *et al.*, 2018).

Power considerations in a node restrict both the amount of processing that can be performed and the frequency of data collection and transmission, and further determine the type of wireless connectivity (KJELLBY *et al.*, 2018). In most cases, device nodes depend on intermediate gateways to receive data and forward them to a centralized server. Bluetooth Low Enery (BLE), Long Range Wide Area Network (LoRa), SigFox-based and even WiFi (IEEE 802.11) are some examples of widely used protocols. Thus, the choice of the communication layer mainly depends on costs, range requirements, external architecture, data density and, of course, on power availability.

With that said, the trade-off between energy consumption and energy availability must be assessed considering low-power devices, the appropriate communication layer, energy harvesting sources and devices, as well as energy storage and management components. The following subsections discuss these aspects under power restrictions.

2.3.1 Energy Harvesting

The concept of energy harvesting generally relates to the process of using ambient energy, which is converted primarily (but not exclusively) into electrical energy in order to power small and autonomous electronic devices as the ones discussed in this work. This process is also referred as "power harvesting" or "energy scavenging". As Beeby *et al.* (BEEBY; WHITE, 2010) says, energy harvesting devices should naturally be designed to operate for the lifetime of the system thereby enabling a long term, self powered, wireless sensing solution. Figure 6 exemplifies a generalized block diagram of an energy harvesting sensor node.

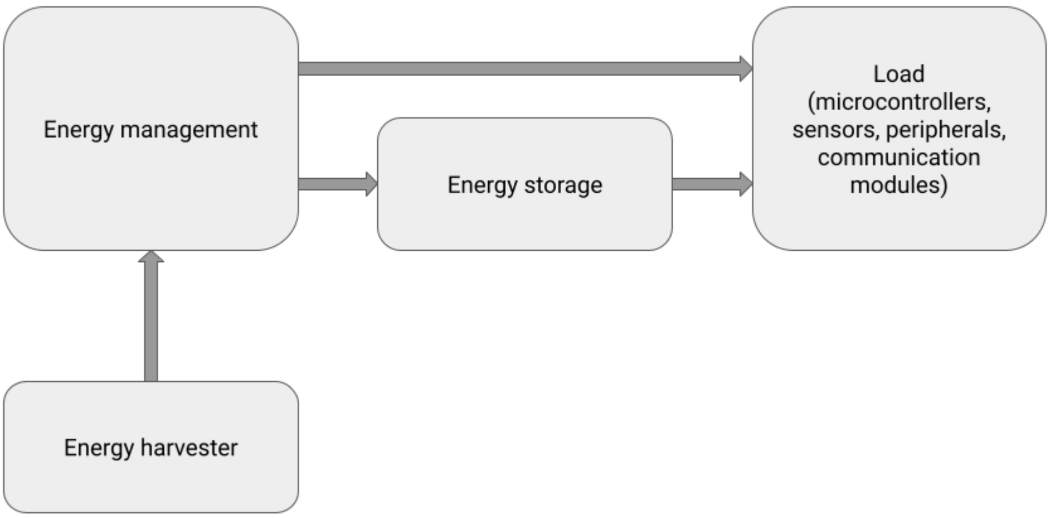

Figure 6 – Generalized block diagram of an energy harvesting sensor node

Different energy domains hover within any typical environment, whether internal or external. For example, in order to harvest electrical energy from an outdoor environment, Sun light can be used to generate electricity, heat can be converted in thermal energy, and motion can turn into kinetic one. The following section presents some examples of energy domains suitable for harvesting demands.

2.3.2 Harvesting Sources

Photovoltaic Energy Harvesting

Photovoltaic (PV) technologies can be the primary power source in environments where light is available. Photons with more energy than the energy gap of some materials (such as a semiconductor in a PV panel), when penetrating such solid, can push electrons from the valence band to the conduction band, which can be then effectively separated through a P-N junction. The same occurs with the respective holes, or gaps, created in the valence band. These separated charge carriers create a surplus of carriers available for conduction in the N and P regions, being thus available to travel as an electric current, through an external load connected to these regions. The more incident photons, the more energy is generated. This is the fundamentals of how solar cells converts light into electrical energy. Some common small devices examples using these cells are calculators, parking meters, weather stations, telephone boxes, and traffic information systems.

Outdoors, the sun can provide around 100 mW/cm2 of optical irradiance, a cloudy day will provide around 10 mW/cm2, and around 0.5 mW/cm2 will be incident on most surfaces within a well-lit room. The very best photovoltaic cells can be up to 40 % eficcient, however, typical ones have efficiency values in the range of 5-20 % under standard conditions. Figure 7 brings a detailed PV cells efficiency report from NREL (NREL, 2021), based on the highest confirmed conversion efficiencies for research cells since 1976, for a wide range of photovoltaic technologies.

Briefly discussing technical behavior, Figure 8 reveals a graph with the I-V characteristics of an ideal solar cell in darkness (darker, upper curve) and under illumination (lighter, lower curve). Based on the referred figure, one can see that if the quantity of

[1] source Adapted from (NREL, 2021)

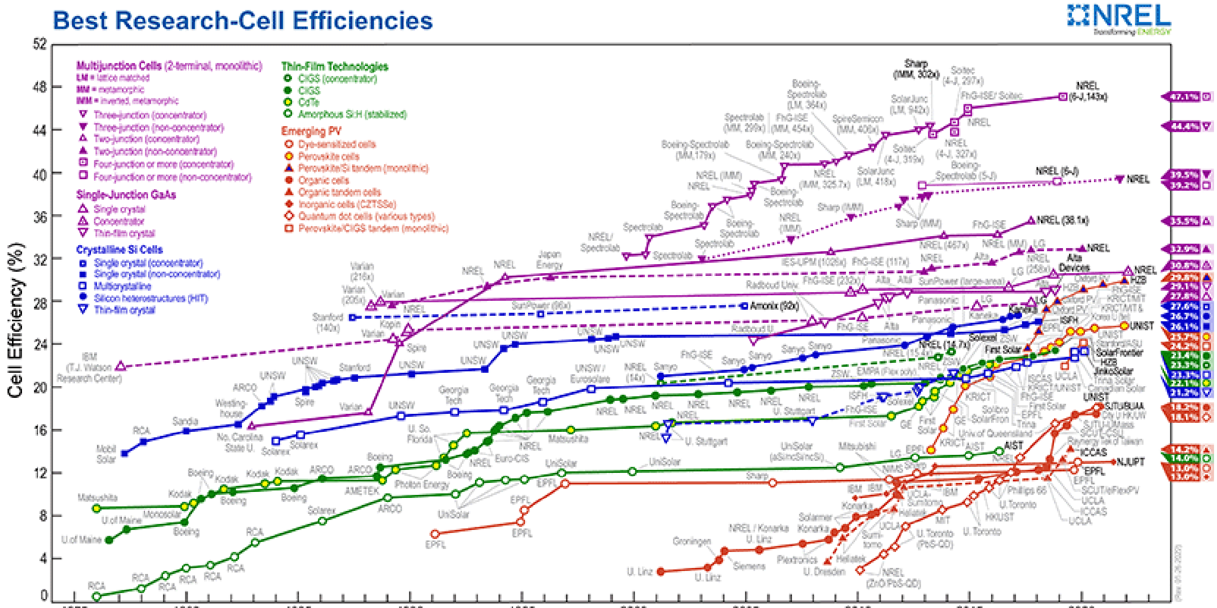

Figure 7 – PV Cell Efficiency Chart [1]

incident photons increases, the lighter curve moves downwards, meaning that the generated energy at the maximum power point also increases.

The simplified equivalent circuit of a solar cell is presented in Figure 9, consisting of a current source producing a current I_L and a diode, representing the P-N junction, that imparts the characteristic I-V behavior of such a cell. The actual current, I, that flows through the load, depends on a series of loss mechanisms within the cell and contacts and on the operational point on the curve, that depends on the impinging irradiance and on the load. A detailed characterization of photovoltaic panels is derived by Dittrich in the first chapter of his book “Materials Concepts for Solar Cells” (DITTRICH, 2014).

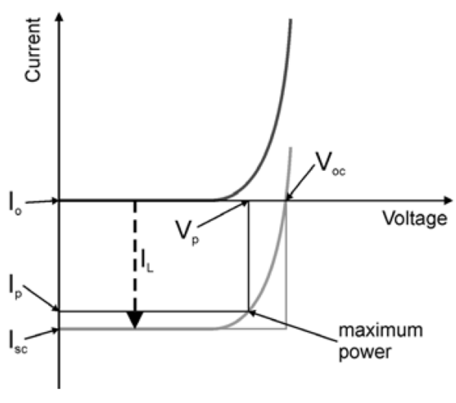

Figure 8 – The I-V characteristics of an ideal solar cell [2]

[2] source Adapted from (BEEBY; WHITE, 2010)

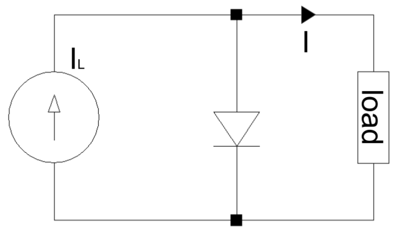

Figure 9 – The equivalent circuit for an ideal solar cell

Kinetic Energy Harvesting

Kinetic energy harvesting, in this context also known as vibrational energy, makes use of vibration-powered generators, which commonly corresponds to inertial spring and mass systems. Kinetic energy can be harvested from a variety of nice applications, such as devices attached to the human body in motion, industrial machinery, transport assets and civil structures.

Three transduction methods can be exploited to extract mechanical energy from the system and provide electrical energy: piezoelectric, electromagnetic, and electrostatic techniques. A brief explanation on the principles of each technique is presented in the items below, as discussed in details by Beeby and others (BEEBY; WHITE, 2010):

- Piezoelectric generators use active materials that generate an electrical charge when stressed mechanically. This type can be used in impact-coupled, resonant, and human-based devices;
- Electromagnetic generators operate on the principle of electromagnetic induction, which arises from the relative motion of a conductor moving through a magnetic flux gradient. Examples are large-scale discrete devices and wafer-scale integrated versions;
- Electrostatic generators employs the relative movements between electrically isolated charged capacitor plates to generate energy. The harvested energy is provided by the work performed against the electrostatic force between the plates.

These types must be chosen considering the size, power and implementation constraints. An interesting field of research under development is the microscale implementations of such techniques. On this sense, (BEEBY; WHITE, 2010) discuss that

> Microelectromechanical systems (MEMS) comprise mechanical and electrical functionality fabricated at the microscale. They combine microelectronics with micromachining processes to realize microscale mechanical components. MEMS inertial accelerometers are a commercially successful device that, given the similarity between these and vibration energy generators, point to the potential for realizing MEMS vibration energy harvesters. This is attractive from the point of view of simultaneously mass-producing microelectronics, microsensors, and a power supply on a single substrate providing a self-powered wireless sensor chip solution.

Thermoelectric Energy Harvesting

Thermoelectric devices have potential applications in thermal energy harvesting, since such energy modal is ubiquitous and found in almost any environment. This type of harvesting takes advantage of thermoelectric effects such the Seebeck effect, the Peltier effect, and the Thomson effect, which describe the interaction and conversion between heat and electricity in solids. Some examples of how thermal energy can be availed are vehicle exhausts and radiators systems, industrial process (such as cooling water from steel plants), geothermal from undergrounds, the temperature gradient in the oceans, and even the temperature difference between human skin and its surrounding environment.

Radio Frequency Energy Harvesting

The wireless power transfer (WPT) techniques are attracting attention due to its potential to feed isolated low power devices, and to even provide ultimately battery-free wireless networks. Rectifying antennas, also known as rectennas, the core of WPT, are built simply by a receiving antenna and a rectifier circuit. These devices can convert Radio Frequency (RF) energy to electrical DC energy, and its applications range from implanted medical devices to smart buildings.

Rectennas can be used to collect energy from ambient radio frequency waves, or from a dedicated source. They are categorized based on two main criteria: the antenna-rectifier impedance bandwidth and the antenna's radiation properties, which should match with the ambient and its specific conditions (WAGIH; WEDDELL; BEEBY, 2020).

Other possibilities with dedicated Energy Harvesting Sources

The energy sources in a harvesting project might be intrinsic to the ambient or not. Sun light, geothermal energy, or already deployed RF waves are some examples of energy sources that can be available in the surroundings of a device. Once the proper way to capture and convert the energy is defined, the harvesting flow can be built to start feeding the device.

However, in some different scenarios, one might want to build a dedicated energy source to feed devices. This perspective can use the same transducers for energy harvesting, but requires a new element: a dedicated energy source, which then delivers power to the harvesting module. Some possibilities are: dedicated RF source, electromagnetic induction with nearby coils, and deliberate remote targeting of light (such as lasers). As a practical example, Ha *et al.* (HA *et al.*, 2015) present a biomedical application in which energy can be supplied to the injected biomedical devices through either wireless power transfer from outside the body, or using harvesting technologies such as RF, heat and vibration.

Comparing Energy Harvesting Sources

Table 2 compares the power density per volume of total system for some common used energy harvesting technologies. As shown in the comparison, one can see that photovoltaic sources in outdoors have the most affordable power density per volume, leading us to choose this type to build the here referred prototype system. The photovoltaics power capabilities are much more modest in indoor scenarios; nevertheless, even indoors lighting enables energy harvesting to feed low-power nodes in less demanding operational conditions.

2.3.3 Power Management

Power management routines are of great importance in a low-power perspective. The ability to convert, control and provide power to the load with efficiency is a key task in a self-powered device. BQ25570 from Texas Instruments is an IC with such capabilities, and more details are shown as follow.

Energy Harvesting Technology	Power Density Per Volume of Total System (W/cm3)
Photovoltaics (outdoors, = 15% cell, 100 mW/cm2 incident irradiance)	15000
Photovoltaics (indoors, = 6% cell, 0.5 mW/cm2 incident irradiance)	30
Piezoelectric (shoe inserts)	330
Vibration (small microwave oven)	116
Thermoelectric (10°C gradient)	40
Acoustic noise (100 dB)	0.96

Tabela 2 – Power Densities of Various Energy Harvesting Technologies

Source (BEEBY; WHITE, 2010).

2.3.4 BQ25570

BQ25570 (INSTRUMENTS, 2021) is an ultra low-power harvester power management IC from Texas Instruments. The BQ25570 chip is capable of extracting and managing from microwatts (uW) to miliwatts (mW) of power with high efficiency from high impedance sources such as photovoltaic or thermal generators, while maintaining those sources at an optimum power extraction point. It has an input boost charger that uses the Fractional Open-Circuit Voltage (FOCV) logic as Maximum Power Point Tracking (MPPT) method.

The FOCV method (more details given by (FREZZETTI; MANFREDI; SUARDI, 2014)) is an offline algorithm very suitable for low-power applications. The estimation of the maximum-power-point voltage V_{mpp} is related to a fraction of the open-circuit voltage V_{oc}, $V_{mpp} = p.V_{oc}$. It can be proved that the parameter p is slightly constant for almost any level of irradiation. The BQ25570 data-sheet suggests a value of $p \approx 0.8$ for PV cells (configurable trough external resistors).

Another feature of BQ25570 is a battery management system with overvoltage and undervoltage protection, as well as a $VBAT_{OK}$ output to indicate whether the battery voltage is at an acceptable level. The last suitable subcircuit in BQ25570 is a buck converter capable of providing up to 110 mA as output current with regulated voltage, which can be used to power loads.

Most of the described features are configurable with external circuitry, allowing the user to harvest from 0.1 V to 5.1 V at the input while respecting the MPPT configuration, to control the battery level within a range that goes from 2 V to 5.5 V and to provide a constant voltage output from 1.3 V to 5.3 V. For this PoC system, an off-the-shelf evaluation module (CJMCU BQ25570) was used, since its pre-set configuration matches the required setup specs. Figure 10 presents such commercial module.

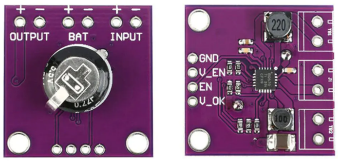

Figure 10 – BQ25570 commercial module

2.4 *Energy Storage*

Energy storage, in our scenario, is a module responsible for keeping the load powered when there is no sufficient harvested power. Storage is usually made by batteries and super-capacitors, and it is a bottleneck of concern when aiming at low-power applications.

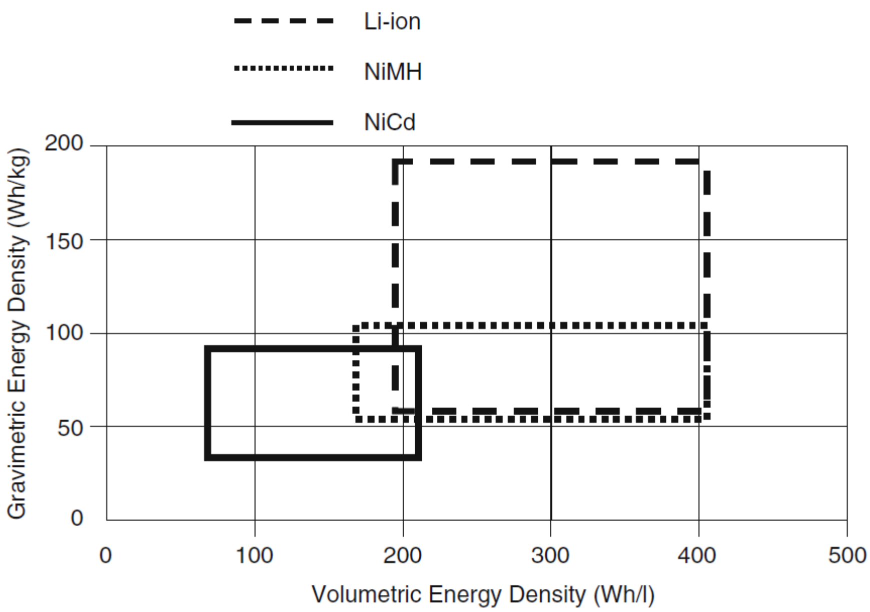

Figure 11 – Performance of common battery technologies [3]

[3] source Adapted from (SNIJDERS, 2005)

2.4.1 Lithium-Ion storage elements

In the sense of rechargeable battery types, as (SNIJDERS, 2005) says, over the last decade the capacity (Wh/kg) of Li-ion type rechargeable batteries has improved by a factor of 4–5 compared to traditional (NiCd, NiMH) types (Figure 11). Lithium-ion cells present very high energy densities up to 200 Wh/kg, and their typical voltage is 3.7 V (RUFER, 2018). These types of energy accumulators are great options for applications with size restrictions, given their high energy density.

2.4.2 Battery Protection IC

Lithium-ion batteries have known fire hazards associated with their energy densities and flammable organic electrolyte. The use, storage, and handling of such cells must comply to strict safety conditions. With that said, in order to protect the cell in the circuit, some protection modules should be used, like the DW01 (CORPORATION, 2021). It is a battery-protection IC designed to protect lithium-ion/polymer battery from damage and to prevent lifetime degradation due to overcharge, overdischarge, and/or overcurrent.

2.5 IoT Platforms

In a distributed system for WSNs, there is usually a server/service side application (either centralized or distributed) to receive, store and provide the collected data to users or external services. This is the “software” part. The IoT edge nodes with sensing capabilities have a path to the destination remote server/service through its communication layer (WiFi, BLE, LoRa, etc), usually passing through an intermediate gateway (depending on the architecture) and using internet traffic to forward data to the other edge.

With the advance of cloud services, there are a variety of web services, e.g. services in Amazon Web Services (AWS) and Microsoft Azure, that focus on IoT implementations, beyond traditional architectures with dedicated servers. These resources are based on standard protocols that allows edge nodes to send packages all the way to its final destination (either a database, an artificial intelligence algorithm, an external web service, a web platform, etc).

2.5.1 Protocols for remote communication

Widely used protocols for internet communication of IoT applications usually relies on the IP (Internet Protocol) stack. Down to the low-level layers, the protocol will depend on the hardware specifications and physical suitable links.

The high-level layers (applications for internet communication) can implement widely used protocols, such as Message Queuing Telemetry Transport (MQTT) and Hypertext Transfer Protocol (HTTP). The MQTT is a lightweight protocol applicable to networks with limited bandwidth. It allows high message throughput for many devices publishing data over the network. HTTP is an application-level protocol for distributed, collaborative, hypermedia information systems. It is a generic and stateless protocol that can allow access to Application Programming Interfaces (APIs), and also allows devices to communicate over internet using standard packages and codes. Besides that, JSON (JavaScript Object Notation) is a common lightweight human-readable data format to compile and interchange data between peers in such protocols.

3 Methodology

At this point, and considering all the elements discussed in the last sections, a base architecture of a self-powered IoT device has been drawn, following the systematic approach presented in Figure 12.

First, there is an energy harvesting sub-system composed by the energy collector, a power management unit and a storage unit. This sub-system provides power to the load, which can be simply a MCU coupled to a sensor (or actuator in some cases) and a communication layer. Last but not least, the communication layer then heads to an online service/server/node which deals with the received data or sends actuators commands. A gateway (e.g. router) is usually placed between the embedded system and the online service to interface and forward packages.

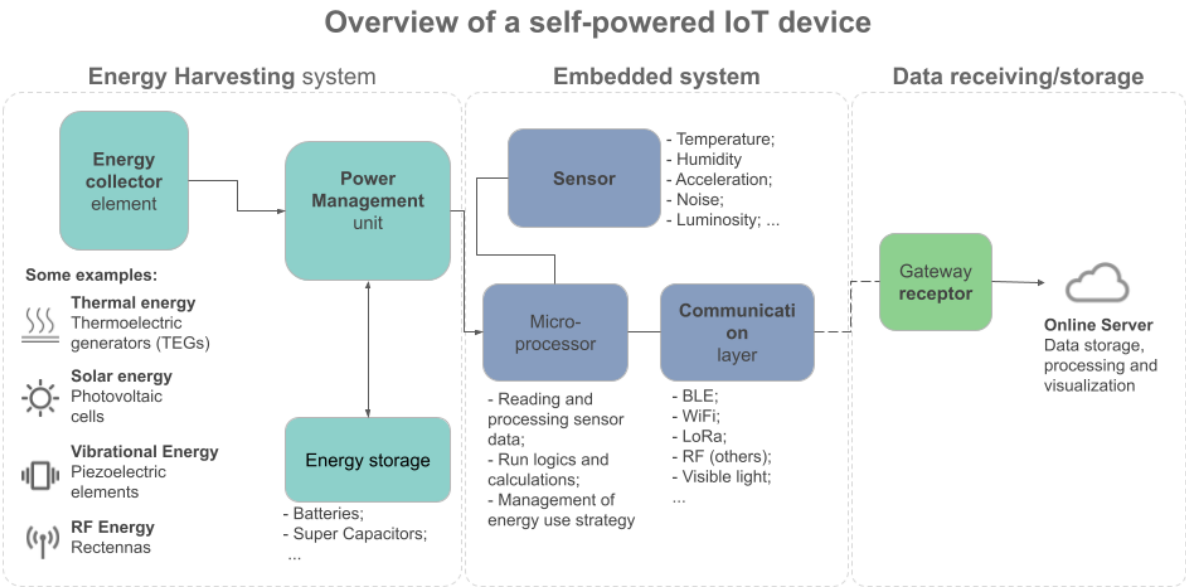

Figure 12 – Overview of a self-powered IoT device

3.1 System Architecture

Translating the previously mentioned overview (as seen in Figure 12) to an executable hardware piece, a Proof-of-Concept (PoC) system was developed to analyse and test the main modules of a self-powered and self-adaptable IoT device. Figure 13 presents the main parts that build up the system.

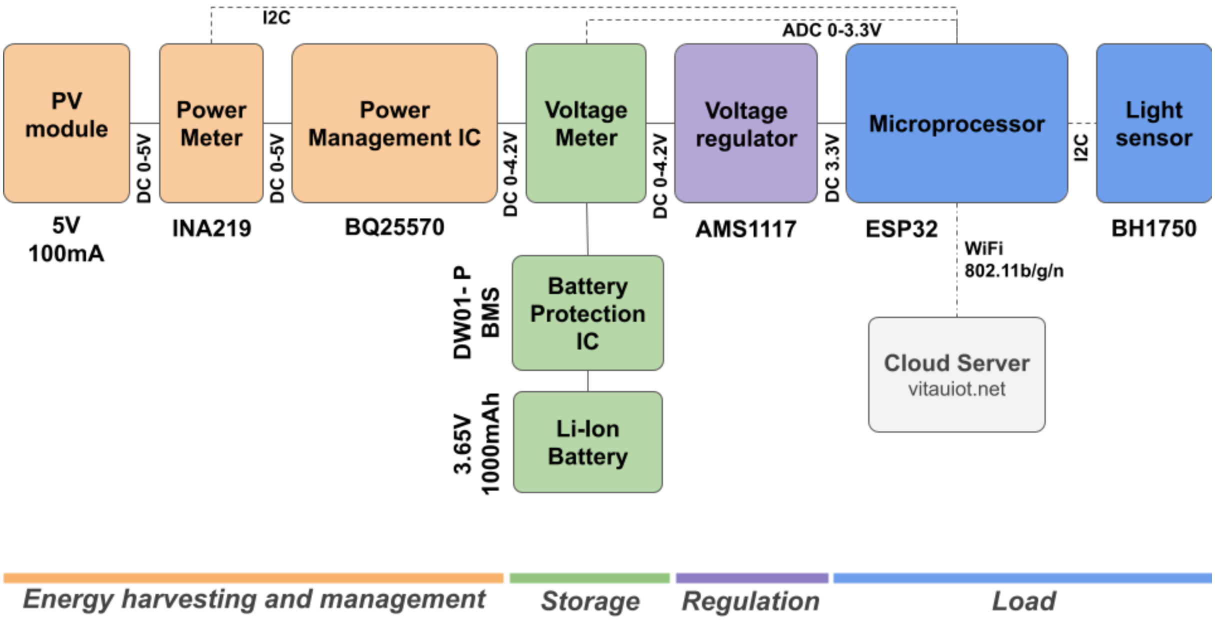

Figure 13 – System Architecture

This system is able to harvest energy from a photovoltaic (PV) source, store it in a lithium-ion battery, and power a microprocessor with an internal WiFi 802.11b/g/n communication module and an external light sensor. This PoC system is then able to connect to a router and send data periodically to a remote online server (vitauiot.net) via HTTP requests. In order to get the main behavior of the running system, four sensing nodes have been incorporated to collect some key parameters: current and voltage of the PV panel, battery voltage, and ambient light. These data are periodically received and stored in the online server.

There are four main modules, namely: i. Energy harvesting and management; ii. Storage; iii. Regulation; and iv. Load. Their parts are discussed in detail in the next section.

3.2 Internal modules

This section presents details on each part of the PoC system. It is important to mention that this work has focused on the system-perspective rather than the modules-perspective. It means that, even if better and more efficient internal modules can be used, this project intends to deliver a systematic analysis of the energy balance independently of the chosen internal modules, serving as a reference for future different design decisions.

3.2.1 Energy harvesting and management

The energy harvesting and management module is based on BQ25570, as presented in 2.3.4. As a power source, a 5 V/100 mA monocrystalline silicon photovoltaic panel is used (75 mmx60 mm in size), with the benefits of such choice being stated in 2.3.2.

A power meter IC (INA219), as shown in 2.2.2, was inserted between the PV source and the BQ25570 IC (see Figure 14). It measures the instant current and voltage of the PV panel, and communicates with the microprocessor through an I2C (Inter-Integrated Circuit) bus (see subsection 2.1.3).

Since the power meter IC is placed between the PV panel and the BQ25570 with MPPT circuitry, one might think that the power meter module may interfere on the impedance seen by the MPPT logic when looking for the maximum-power point. However, as seen in 2.3.4, the BQ25570 module implements a MPPT algorithm with FOCV method. Since this method is based on estimation of the maximum power change observing the variation of the open-circuit voltage, the power-meter circuit is not expected to significantly influence the performance of the MPPT due to an impedance change.

3.2.2 Storage

A lithium-ion battery is used as an energy storage element, considering its advantages discussed in 2.4.1. The chosen battery is the LIP1522 from Sony, with 1000 mAh capacity and a nominal voltage of 3.65 V. Its maximum charge current is 1 A, and the maximum charge voltage is 4.25 V. Other common options can be used such as the 18650 cells.

As a protection circuitry, the DW01 is used (details in 2.4.2). On its turn, a voltage divider was used as a battery-level detector, to reduce the output battery voltage to the levels of the microprocessor analog-to-digital converter (ADC), as will be discussed in subsection 3.2.4.

3.2.3 Regulation

Voltage regulation aims to deliver proper voltage levels to the microprocessor. A commercial module featuring ESP32 was used in this PoC system, and has both the microprocessor itself and a built-in voltage regulator (see 2.1.1).

The regulation module plays an important role in the total power consumption of the system. Low-Dropout (LDO) regulators are suitable for the mentioned applications due to the low-voltage working levels. The regulator soldered in the used module is the AMS1117 (MONOLITHIC, 2021), nonetheless, there are many other better options for a final architecture. These other regulators can be considered, while the AMS1117 has been the benchmark in this project.

3.2.4 Load

The system load is basically a microcontroller unit (MCU) and an ambient light sensor IC. The microprocessor is the ESP32 as presented in 2.1.1, and the light sensor is the BH1750, as in 2.2.1.

This project makes use of the ESP32 deep-sleep mode with a wake-up timer to leave the device in the standby status (and consequent low power) between active intervals (as discussed in subsection 2.1.2).

The communication layer is the WiFi 802.11 b/g/n. Since WiFi routers are widely available in a variety of environments, devices using this technology are easy to deploy and use the plug-and-play approach. Also, there is no need for extra equipment (such as Bluetooth or LoRa gateways). The typical WiFi range at 2.4GHz is up to around 100 m. Despite not being the communication layer with the leanest energy consumption, WiFi is still relevant for IoT applications in homes, offices, shopping centers and industries and, of course, for this laboratory validation.

After being connected to a router with internet access, the PoC device is programmed to connect and periodically send data to a virtual online server, the vitauiot.net Platform from Vitau Automation, an automation based company (LTDA, 2021). The server is located in North Virginia, USA, from Amazon Web Services.

To measure the battery level as stated in subsection 3.2.2, one ADC input of ESP32 has been used. It has a 12-bit resolution, and a simple voltage divider is used to halve the battery voltage, which is then read by the corresponding ADC converter (3.3 V max). Two 1-MΩ resistors were used as the voltage divider, to downscale the battery voltage by a factor of 0.5 (see wiring in Figure 14).

The ESP I2C bus is used to establish serial communication with both the PV power measurement unit (INA219) and the BH1750 light sensor. Both INA219 and BH1750 are powered by the ESP32 GPIO19 (wired to the corresponding sensors VCC pin, as seen later in Figure 14). This GPIO is set to 3.3 V as soon as the device initiates the active mode; in idle mode, GPIO19 is set to 0 V, thus turning off such sensors. The total current demanded by both sensors (2 mA) is properly supported by the ESP32 GPIOs (40 mA), so there was no need to use an intermediate transistor. One might use enable pins (if available) to activate and deactivate these sensors in a more elegant way, but there were no external connections for such pins in the commercial modules used here.

3.2.5 Circuit schematic

The interconnection between the previously mentioned parts are shown in Figure 14.

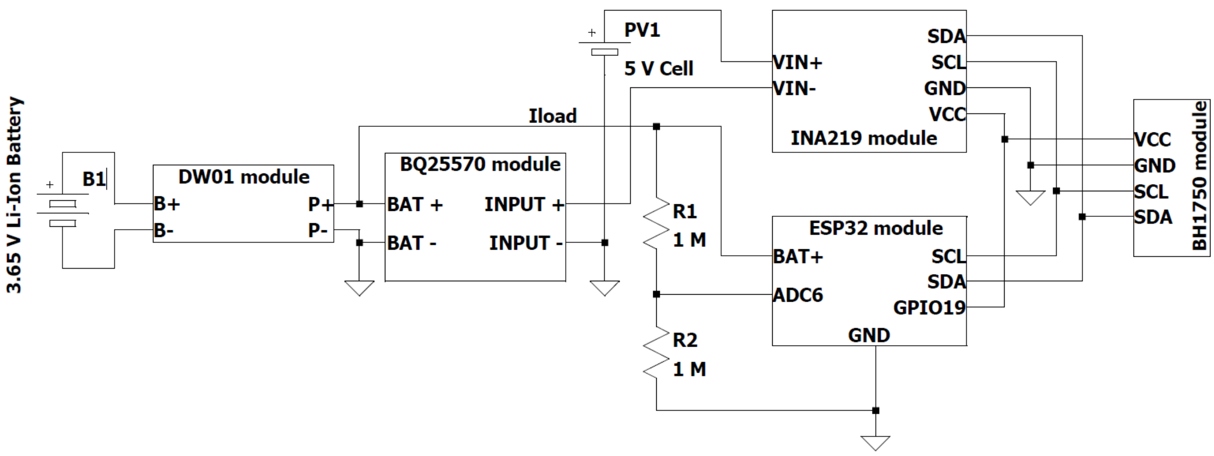

Figure 14 – Circuit schematic

3.2.6 Data transfer

The data transfer uses a HTTP client developed in the ESP32 firmware. This client makes HTTP POST requests to the online server at vitauiot.net (with proper authentication logic using tokens), which in turn receives and stores the information. The following code block presents the data format using the JSON standard (2.5.1), as an example of the package payload that goes from the ESP32 to the remote server.

```
{
device_id: "myId",
pv_current_mA: X.X,
pv_voltage_v: X.X,
battery_voltage_V: X.X,
illuminance_lux: X.X
}
```

Each package is received by the server, linked to the receiving timestamp, and the full data is saved in a database. This information can be extracted to a CSV (Comma Separated Values) file, and be then analysed with math tools as will be shown in the results chapter.

3.3 System Characterization

After being designed and built, the proof-of-concept device was characterized from the energy perspective, with the aim of obtaining both the consumption and generation profiles. The former is based on the load power over time (MCU and sensors), considering the cyclic behavior of its operation (collecting/transmitting data, sleeping, and then repeating it all over again). The logic implemented in the MCU directly affects the power consumption over time, as different tasks have different energy demands. The latter corresponds to the generated power over time in a period of interest (a day, as in this project). As shown previously, the greater the incidence of light, the more power is delivered to the load (reaching peaks around noon time, for a solar panel in outdoors, as in this case). With the characterization of both consumption and generation profiles, one should define the relationship between them and, ultimately, the best configuration to balance them within a self-powered device. This is the discussion in the next section.

3.4 Energy balance

One of the main goals of this project is to develop a wireless module that assesses the balance between generated and consumed energy, during a certain period of time, adapting its data regimen according to the best balance scenario.

The active time of the module is when there is most of the power consumption, hence, the occurrence of active intervals impacts directly on the overall energy demanded by the load. Many applications do not demand too frequent data collection, processing and transmission. In some cases the module can be programmed to sparsely measure and send information throughout the day, and in others it is only woken up when an occasional triggering event happens. This duty cycle is then low and the transceiver can afford to be in the idle state for most of the time, assuming that proper sleep disciplines are adopted (WERNER; RABAEY; AARTS, 2005). The longer the idle time between active periods, the lower the overall consumption throughout the day. The ESP32 deep-sleep mode can be used to reduce the power consumption during the inactive time, with a yet non-zero but ideally minimum load current.

From the balance perspective, the total energy required by the system over a period of time encompassing a certain number of cycles, containing both the active and idle times, must not exceed the energy generated by the harvesting source during that same period. Therefore, a data diet, i.e. the amount and frequency of data is fed into, processed and purged out of the module, must be compliant to the available energy.

The amount of data can be controlled, for example, by the number of different data points, or sensors, and number of samples to be collected in an active mode, e.g. one temperature and one humidity sample or, if under restricted conditions, just one temperature sample. On the other hand, the frequency of data collection corresponds to intermittence of their transmission, i.e. the number of active modes comprised in a period of interest, separated by a time T_{idle}, or standby time. In this work we control the data diet by adjusting that frequency of active modes. No amount of data per active mode is controlled at all, but would be a fine tuning suitable for other developments.

Considering the data-diet adjustment by controlling the frequency of active modes, an equation was derived to calculate the consumed energy by the load per period T, which is split into active and idle times ($T = T_{\text{active}} + T_{\text{idle}}$). The equation for this consumed energy E_C, in W.s (or J), can be written as:

$$E_C = P_{active}.T_{active} + P_{idle}.T_{idle}[\text{W s}] \tag{1}$$

For a proper match with measured data, as shown later in subsection 4.0.1, the last equation can be rewritten in a convenient way as a function of the average energy spent during an active stage (E_{active}) in W.s, the load power in the idle stage (P_{idle}) in W, and the idle time (T_{idle}) between active stages, as expressed by (2).

$$E_C = E_{active} + P_{idle}.T_{idle}[\text{W s}] \tag{2}$$

E_{active} and P_{idle} are assumed as uniform values throughout periods since the device performs the same actions repeatedly. Some variations might occur due to transmission latency, logic conditions or triggers and others, however, the respective average values are practical approximations in most scenarios, including this current one.

The total energy consumed per day can be calculated using (3). It is simply (2) multiplied by N, the number of periods/cycles in a day ($N = 86{,}400/T$, i.e. the total seconds in the reference time range divided by T, given in seconds).

$$E_{day} = N.E_C = \frac{86,400.E_C}{T}[\text{W s}] \tag{3}$$

Using (2) in (3), (4) shows then the calculation of the consumed energy per day (E_{day}), based on the periods T_{active} and T_{idle} in seconds, the energy spent per active mode (E_{active}) in W.s, and the load power in the idle mode (P_{idle}) in W.

$$E_{day} = \frac{86400}{1 + T_{active}/T_{idle}}.(\frac{E_{active}}{T_{idle}} + P_{idle})[\text{W s}] \tag{4}$$

As an interesting parameter, one can call the ratio $T_{\text{active}}/T_{\text{idle}}$ as the "active proportion", A_{p}, i.e. the amount of active time compared to idle time. Also, to accomplish an energy balance within a day, E_{day} must be less or equal to the daily generated energy (E_{gen}), which changes according to the solar conditions throughout a given day. Equation (4) can then be rewritten as (5):

$$E_{gen} >= \frac{86400}{1 + A_p}.(\frac{E_{active}}{T_{idle}} + P_{idle})[\mathrm{W\,s}] \tag{5}$$

Considering the mentioned low-power restrictions, we can assume that the device must remain most of the time in the idle mode, then

$$T_{\text{idle}} \gg T_{\text{active}}$$

which means A_{p} is very close to zero. Equation (6) simplifies (5) in theses cases: first, assuming $A_{\text{p}}{\approx}0$ and taking it out of the equation, then conveniently isolating $\mathrm{T_{idle}}$ to the left side:

$$T_{idle} \geq \frac{E_{active}}{\frac{E_{gen}}{86400} - P_{idle}}[\mathrm{s}] \tag{6}$$

Equation (6) compiles the calculation of the minimum $\mathrm{T_{idle}}$ (or deep-sleep time) for a device with idle load power $\mathrm{P_{idle}}$, average energy spent per active mode $\mathrm{E_{active}}$, given the average generated energy from the harvesting source $\mathrm{E_{gen}}$ in an analysis comprising the time frame of a day.

If one wants to take into account the battery charge-discharge efficiency $\mathrm{bat_{eff}}$, load and PV power variations, respectively Δ_{load} and Δ_{pv}, all given as percentages, (6) can be rewritten as (7).

$$T_{idle} \geq \frac{E_{active}.(1 + \Delta_{load}/100)}{\frac{E_{gen}.(1 - \Delta_{pv}/100).(bat_{eff}/100)}{86400} - P_{idle}}[\mathrm{s}] \tag{7}$$

These equations will be used to estimate the idle time based on measured data (in results chapter to come).

3.5 Experimental Setup

The experimental setup was developed as following:

- Device specification and construction
- System firmware development (using C++ language and Arduino IDE Platform)
- Remote server setup
- System characterization using measurement nodes and real data storage
- Calculations to get the best value for T_{idle} assuming low power conditions ($A_{\text{p}}{\approx}0$)

- Setting device's T_{idle} as calculated
- Data collection for validations
- Results analysis

4 Results and Analysis

The results from the mentioned solution are presented in this section. Based on the internal parts specified and designed as in 3.2, the prototype system is depicted in Figure 15.

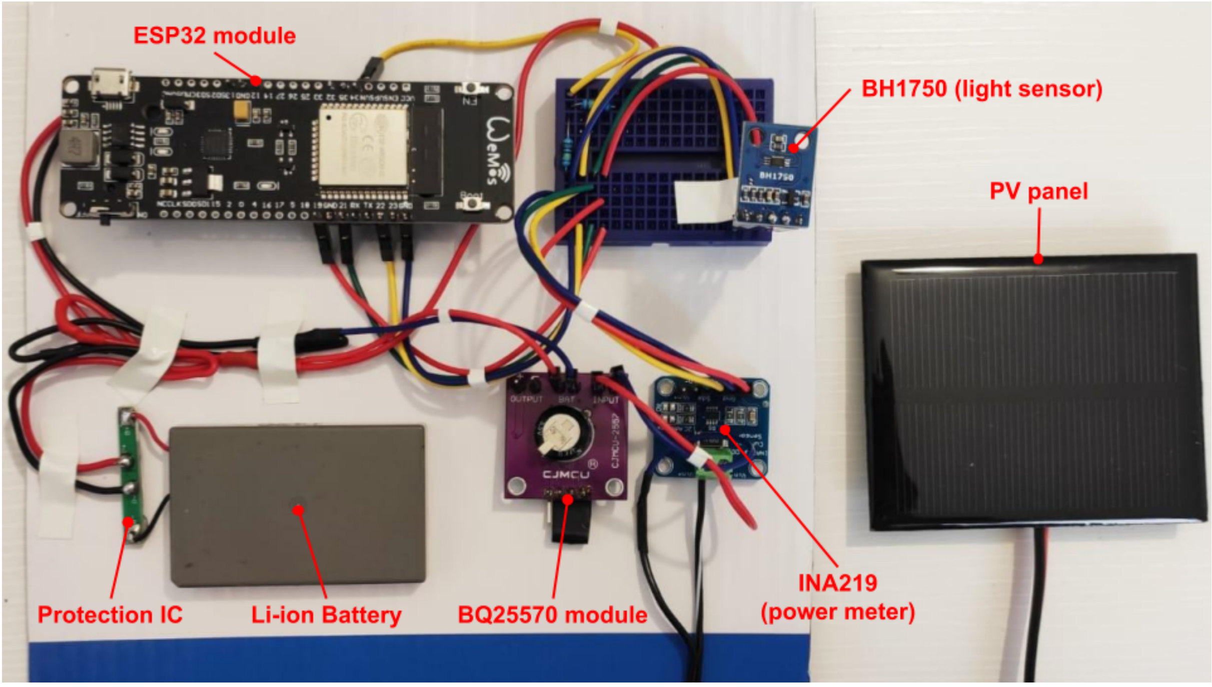

Figure 15 – Full Prototype System

This system was submitted to a real case condition, in which it was exposed to Sun light in some periods of a day (some obstacles caused shade after specific times). The device was programmed to perform its functions as designed: (i) connect to an available WiFi network provided by a router with internet access, (ii) read data from sensors, (iii) send data to the remote server, and (iv) call sleep mode for a period T_{idle}. The best value for T_{idle} was calibrated as will be shown here by using the previously discussed equations in 3.4. The complete system was then validated during three days with registered data going to the remote edge, as in a real IoT flow.

4.0.1 Load power characteristics

The load (MCU and sensors) was monitored to detect its power demand both in active and idle modes. This data was collected by using a separate INA219 module connected to a separate ESP32 module, independent of those equivalent modules in the main system, with data being transmitted to a computer via USB-serial communication. The load current and voltage references correspond to the mesh labeled as I_{load} in the circuit schematic shown in Figure 14.

Figure 16 presents the load power over an example period, with two evident active modes. It is clear that the idle power is approximately constant, while the active mode power can have varying profiles on each cycle.

Figure 17 details the superposition of other four example curves of load power over time during specifically active stages. One may see that the average duration of active modes is around 7.7 s (by considering the active times pointed by the black arrows), and some peaks reaching 2.5 W on the power profile are also evident in some cases. These variations are expected due to data flow oscillations, logic conditions, RF communication, connection retries, network latency, etc.

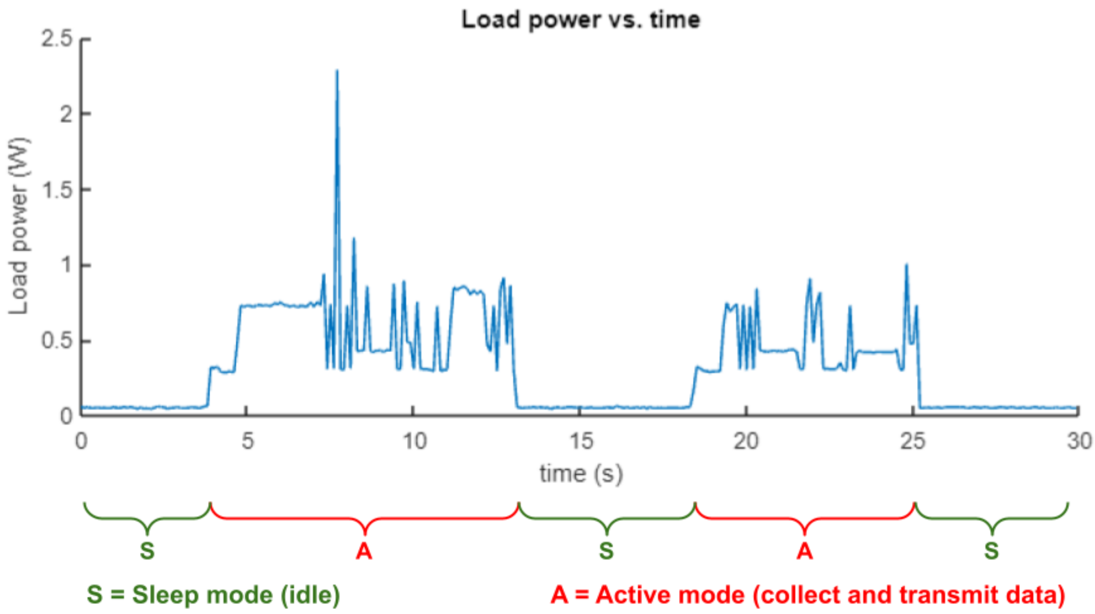

Figure 16 – Load Power Profile

The idle power P_{idle} is pretty constant and predictable around 51 mW, and the energy spent on each active cycle E_{active} is on average 3.43 W.s. This value was approximated by taking the integral of power over time during active cycles, and assuming the average value for these four sample curves. The calculated energy per active mode is shown in the corresponding labels in Figure 17.

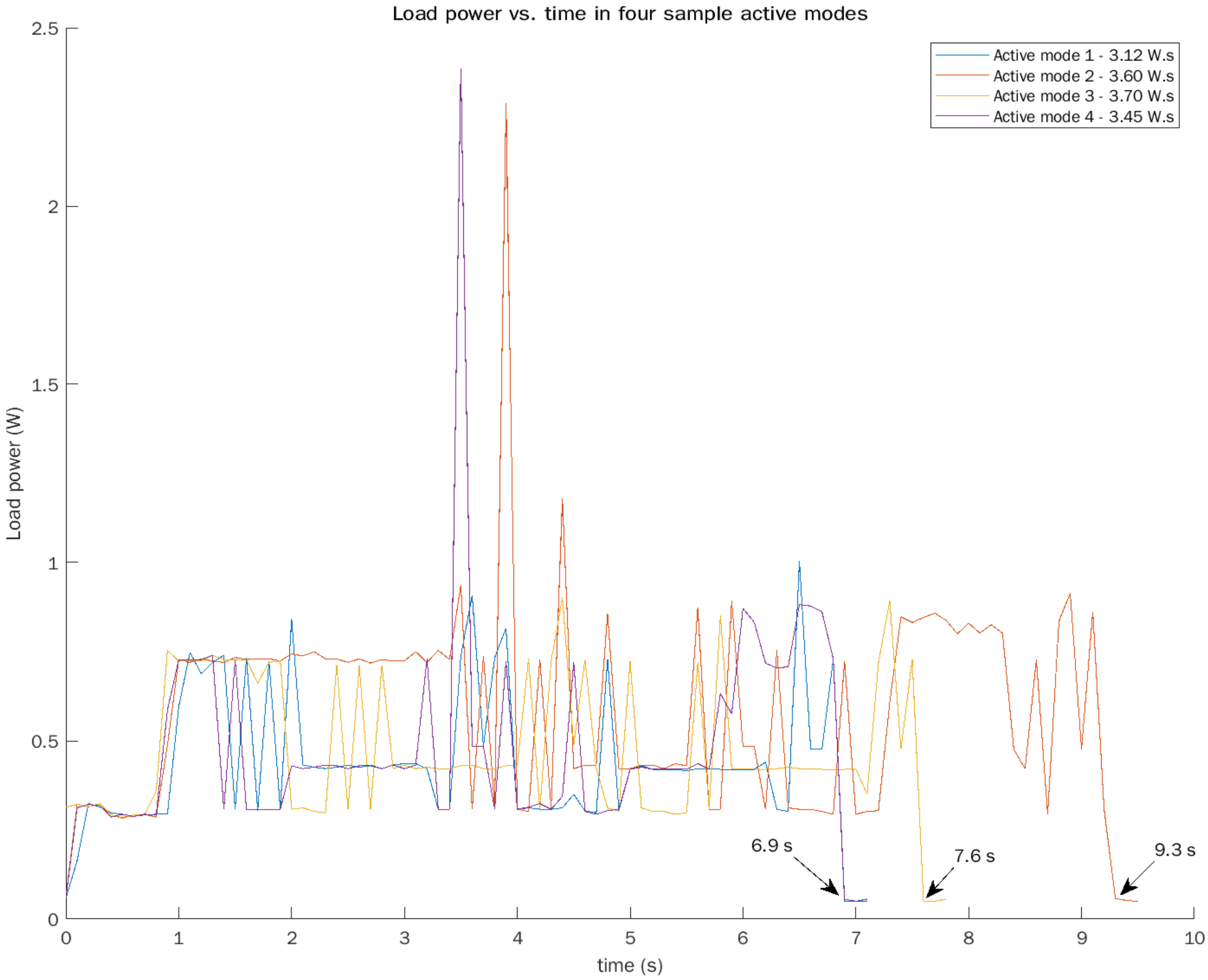

Figure 17 – Load power (active mode) comparison

4.0.2 Energy generation

The energy harvesting and storage modules were monitored in order to register the power of the PV cell and the voltage of the battery over time.

The PV cell was placed in a configuration where it receives some direct and diffuse sunlight. Figure 18 presents the PV power and battery voltage for a measured range of three days (upper graph), comparing it to the respective illuminance readings from the BH1750 sensor (lower graph). The latter was placed in a position different to that of the PV cell and was subjected to diffuse Sun irradiation. However, as the weather was mostly overcast, the irradiance profile on the solar cell and on the illuminance sensor should offer a close match, as verified in the same Figure 18. External noises on the battery voltage detector (ADC converter) were suppressed by using a low-pass filter. On the other hand,

Figure 19 presents the PV instant voltage, current and power variations for the same period.

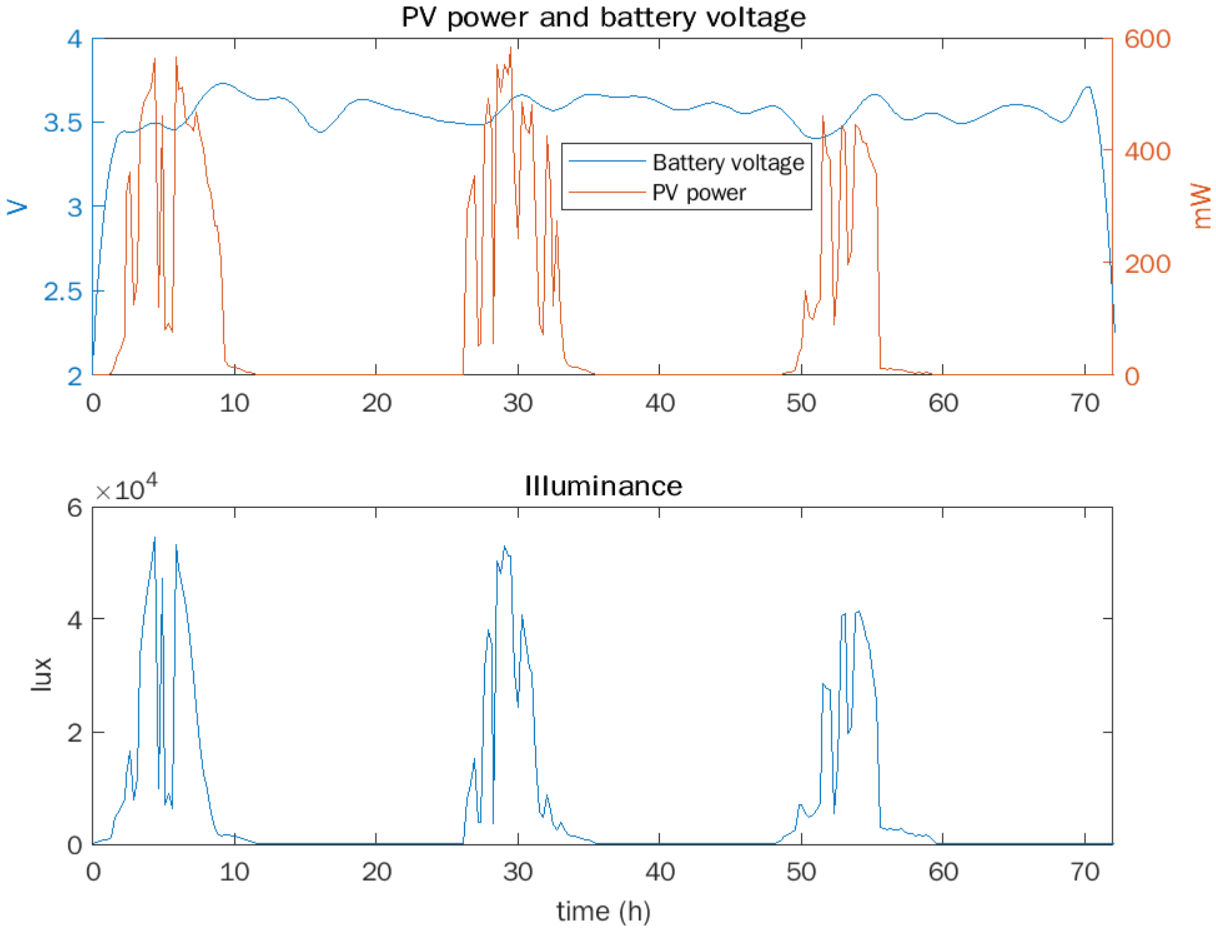

Figure 18 – PV power, battery voltage and illuminance

From the collected data, the system in such conditions is able to produce approximately 7,856 W.s per day, average. Considering this value and the load demands discussed in the previous subsection (4.0.1), one can use Equation (7) to estimate the minimum time T_{idle} between active stages. Using (7) and assuming low power conditions (i.e. $A_p \approx 0$, then the device spends much more time on standby than on active modes), the calculation gives a $T_{idle} \approx 22.1$ minutes, promoting the balance between generation and consumption in the system. This procedure takes into account a battery charge-discharge efficiency of 85 %, load power variations up by 20 % and PV power variation down by 30 %, which are adjustment parameters already discussed in 3.3.

Assuming a value of $T_{active} \approx 7.7$ s (according to 4.0.1), the period time is $T = (T_{idle} + T_{active}) \approx 1333.7$ s, which means that the device will run active modes $N \approx 64$ times per day (86400 s) in such conditions, which also means getting around 64 samples of data

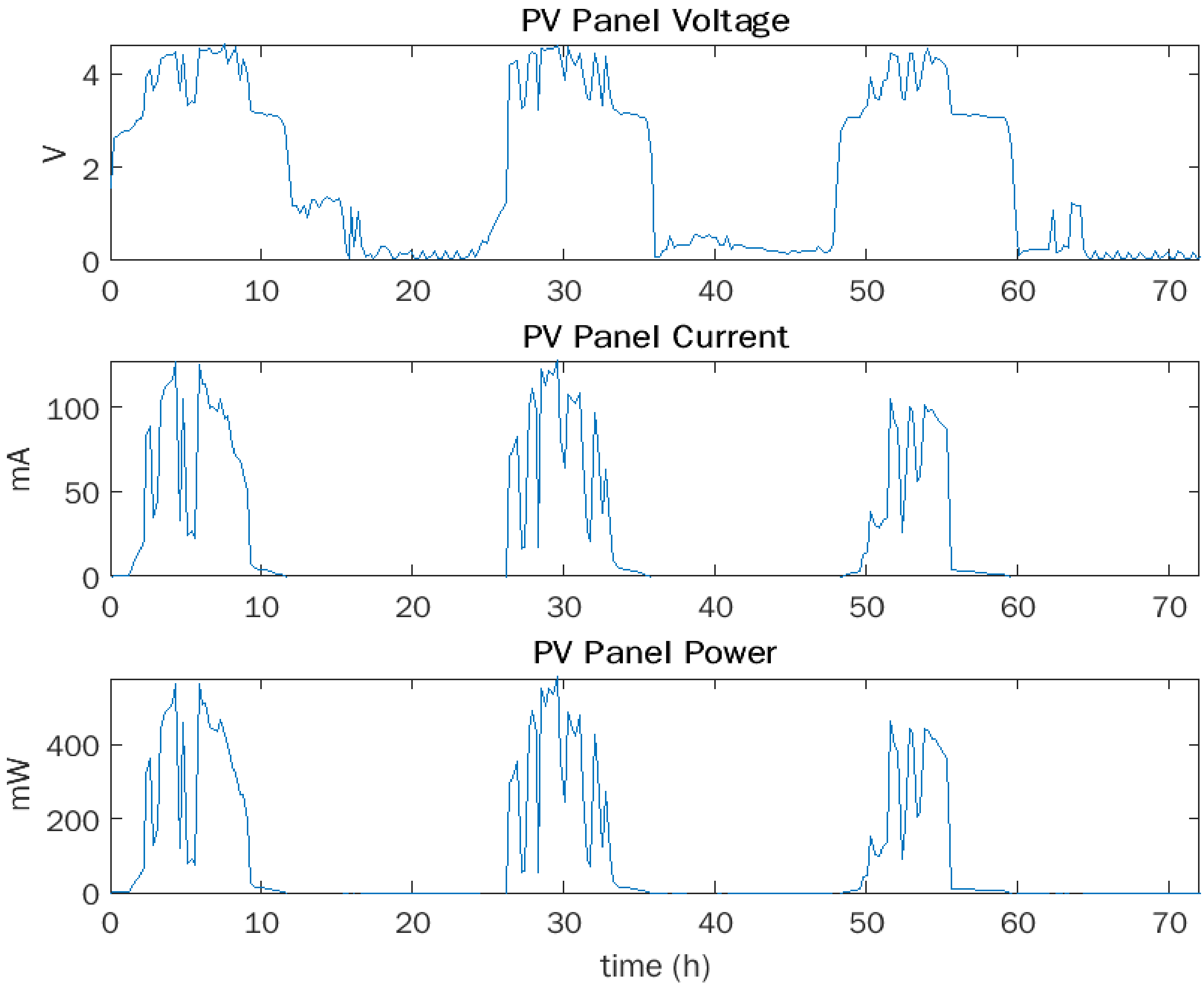

Figure 19 – PV-cell current and voltage

points from the sensors. As a check, one can confirm that $T_{idle} \gg T_{active}(1326.0 \gg 7.7)$, supporting the premise that $A_p = (T_{active}/T_{idle}) \approx 0$.

Thus, the system could act as a self-powered node with an inactive period of around 22 minutes. This value was converted to seconds and configured as the deep sleep time in ESP32 firmware. With that operation setup, the device could execute all of its main functions: read data, connect to the server, transmit data and then run sleep mode until the next active mode begins (timer countdown triggered by T_{idle}).

As Figure 18 suggests, the PV panel feeds the device and charges the battery during sunlight, and the battery takes over at night in a discharge mode to keep the system powered. In the time range of three days, as exemplified, the complete system kept itself balanced as regards energy, thus, keeping itself up and running as expected, even in face of variations in the generation profile.

4.0.3 BQ25570 prototyping board

As a parallel and complementary work, a custom prototyping board to test the BQ25570 chip has been developed at OptMA^{lab}. It was necessary considering the lack of flexibility of commercial prototyping boards for this IC. Some of them prevent, for example, the selection of a specific FOCV percentage in the MPPT circuit, and most of them require resistor desoldering to change other configurations. Therefore, the main goal of this custom board is to be as flexible as possible while keeping the configuration process simple.

The board has four main features: a LED that can be connected to and then monitor the $VBAT_{OK}$ signal; trimpots to configure the IC battery management and output voltages; a supercapacitor that can be used as storage element if needed; and several jumpers to enable different configurations.

The current layout is versatile and enables one to easily change almost every possible configuration of the BQ25570. Using the supercapacitor and the LED, it is possible to simply configure the board with the energy harvesting component, e.g. photovoltaic generator, a multimeter and a screwdriver, without the need for any additional external components or power supplies.

Considering the system in Figure 15, this custom board would replace the BQ25570 module. Some advantages are the possibility to change the power source configuration and to make better use of the BQ25570 battery management. The commercial module currently deployed has the MPPT settings hardwired to a value of FOCV that is suitable for photovoltaic power generation, making it difficult to switch to another type of source, such as a thermoelectric generator, for example, which requires a different MPPT configuration. The battery management system is also preset with soldered resistors on the board, which poses limitations if one needs to use a different storage component with different threshold values.

A rendered view of the designed board with its components is depicted in Figure 20.

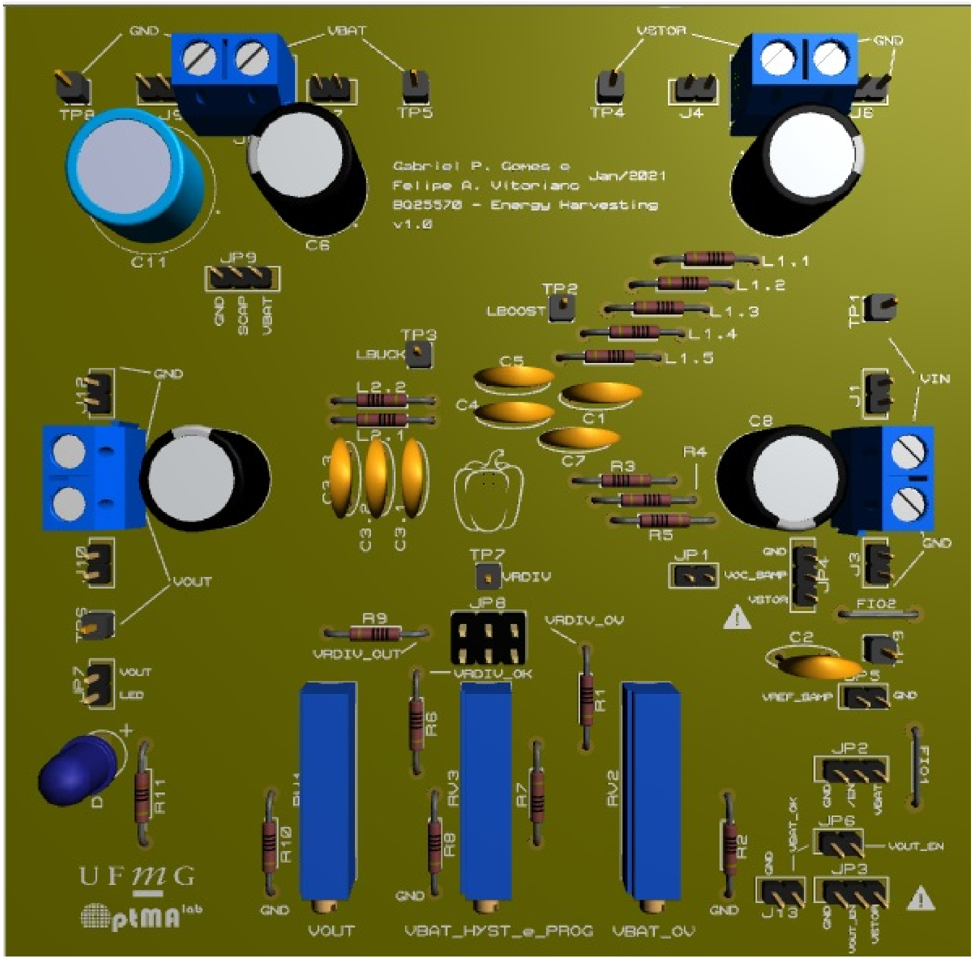

Figure 20 – Rendered design view of the custom prototyping board for the BQ25570

5 Conclusion

The prototype of a self-powered and self-adjustable IoT system has been developed and tested successfully. Although the overall power consumption can still be reduced by hardware improvements, and the load consumption can be adjusted at run time, the tested conditions have shown a variety of possibilities to develop and improve devices with the mentioned characteristics.

The derived equations that characterizes the energy balance in such system are consistent and match with the experimental recorded data. By configuring the MCU's sleep time according to the calculated idle time as mentioned, the device can operate independently of external sources, while sending collected data (PV panel power, battery voltage and ambient illuminance) to the online IoT server through a standard WiFi connection.

From the collected data presented in 4.0.2 and 4.0.1, and using the respective measured parameters in equation (4), one can estimate the average energy spent by the load per day (considering the real T_{active}≈7.7 depicted in 4.0.1). This gives a value of E_{day}≈4,660 W.s to be consumed by the load per day, which is within the average energy generated by the harvesting module, E_{gen}≈7,856 W.s. The leftover energy is mainly due to the battery charge-discharge and power variations percentages incorporated into the calculations.

In view of the data diet perspective, having in mind the results reported in this work, some topics can be recommended in order to achieve a suitable diet (i.e. the intermittence of data collection/sending) for an energy autonomous system. If one wants to prescribe a data diet to such self-powered device, two approaches should be considered: (i) a demand-based project, or (ii) a balance-based project. The first approach takes into account the load power requirements and the data diet that must be imperatively practiced. Hence the energy source, harvesting technique, energy storage and management modules must be all designed in order to meet these load requirements. The second approach, however, considers the balance between energy generation and consumption. This was the method followed in this project. As seen in the course of this text, one must know, on one hand, the nature of the data to be measured, the type of data transmission, the elements of the system, and how much energy it all requires in active and standby modes. On the other hand, it is also necessary to know the generation capacity of the sources available in the environment as well as the available energy converters and, from that, prescribe the best data diet to the system. It can be done using an energy balance equation, as derived in this work. This gives the best time between active modes, ensuring the adjustable load diet will fit in the capabilities of the harvesting circuitry.

5.1 Applicability

Independent IoT devices are of great use in a variety of scenarios. Agriculture, farms and forest applications are powerful considering the need of spreading measurement sensors in large fields - in which such IoT modules would be suitable. Industries increasingly needs sensing technologies for assets monitoring, thus the referred IoT devices can be interesting since harsh environments do not allow constant interference and maintenance due to safety, operational and costs reasons. Also, smart cites can also take advantage of these technologies to easily deploy smart nodes. Last but not least, our residences, buildings and shopping centers can be more and more controlled if IoT nodes can be distributed in the rooms, without the worry of having to feed them often.

These are just few perspectives and, from the microelectronics point of view, current developments can allow the system-on-a-chip solutions which integrates harvesting, storage, sensing and communication parts in a single chip. The advance of semiconductors, electromagnetic communication and powering, new and more efficient energy transducers, MEMS and small sensors are enabling these novelties.

5.2 Next steps and possibilities

From the discussions and test results, there are some topics to keep working on to achieve the best architecture for a self-powered IoT device:

- The ideal time period between active modes can be calculated at run time by the MCU. Since the power consumption depends deeply on this parameter, the microprocessor can calculate this time and adjust it according to the available energy, knowing the power consumption profile of the load, and the collected energy in the previous 24 hours, or any other time interval of interest. This would be an important feature heading towards a reliable self-adaptable data diet, whereas the device can adjust its own power restrictions to comply to the available energy from its environment;

- This work has shown the control of data diet by adjusting only the frequency of active modes (the intermittence of data transmission). No amount of data per active mode is controlled at all, but this would be a fine tuning to complement and sharpen the energy consumption control, considering data collection restrictions and the possibilities to vary the amount of sensor heads that can be triggered and respective samples that can be taken in an active mode.
- The overall load power can be reduced by using more efficient circuitry (LDO regulators, different physical layers for communication, power management capabilities, etc). This would have a great impact on the load current;
- Other communication layers can be tested, such as BLE, LoRa and even LiFi (Light Fidelity) protocols;
- The indoor photovoltaic energy harvesting capabilities should also be investigated, using the BQ25570 features to deal with extremely low-power harvesting scenarios (knowing that most PV devices are designed and optimized for outdoor use);
- Many complementary energy sources, other than photovoltaic, can be tested, and redundant multi-domain harvesting could be investigated. Thermal electric generators (TEGs), vibrational generators, rectennas are some example of different power sources that can be coupled to this process;
- Other online servers and protocols can also be used to receive and store data, other than the proprietary solution herein mentioned (vitauiot.net). MQTT (Message Queuing Telemetry Transport), for example, is a widely used protocol for IoT applications and is implemented in off-the-shelf solutions available on the market.

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References

AMMER, J.; BURGHARDT, F.; LIN, E.; OTIS, B.; SHAN, R.; SHEETS, M.; RABAEY, J. Ultra-low power integrated wireless nodes for sensor and actuator networks. In: ______. *Ambient intelligence*. First. [S.l.]: Springer, 2005. Cited 2 times on pages 16 e 17.

BEEBY, S. P.; WHITE, N. M. *Energy Harvesting for Autonomous Systems*. First. [S.l.]: Artech House, 2010. Cited 4 times on pages 24, 26, 27 e 30.

CAPRA, M.; PELOSO, R.; MASERA, G.; ROCH, M. R.; MARTINA, M. Edge computing: A survey on the hardware requirements in the internet of things world. *Future Internet*, v. 11, n. 4, 2019. ISSN 1999-5903. Available from Internet: ⟨https://www.mdpi.com/1999-5903/11/4/100⟩. Cited 2 times on pages 15 e 16.

CORPORATION, F. S. *DW01x datasheet*. 2021. Online; accessed 2021-03-05. Available from Internet: ⟨https://www.ic-fortune.com/upload/Download/DW01x-DS-17EN53345.pdf⟩. Cited on page 32.

DITTRICH, T. *Materials Concepts for Solar Cells*. First. [S.l.]: Imperial College Press, 2014. Cited on page 26.

FREZZETTI, A.; MANFREDI, S.; SUARDI, A. Adaptive focv-based control scheme to improve the mpp tracking performance: an experimental validation. *IFAC Proceedings Volumes*, v. 47, n. 3, p. 4967–4971, 2014. ISSN 1474-6670. 19th IFAC World Congress. Available from Internet: ⟨https://www.sciencedirect.com/science/article/pii/S1474667016423840⟩. Cited on page 30.

GARTNER. *Gartner Research and Advisory Reports 2019-2020*. 2021. Online; accessed 2021-04-15. Available from Internet: ⟨http://www.gartner.com⟩. Cited on page 15.

HA, B. W.; PARK, J. A.; JIN, H. J.; CHO, C. S. Energy transfer and harvesting for rf-bio applications — invited. In: *2015 IEEE MTT-S 2015 International Microwave Workshop Series on RF and Wireless Technologies for Biomedical and Healthcare Applications (IMWS-BIO)*. [S.l.: s.n.], 2015. p. 54–55. Cited on page 29.

INSTRUMENTS, T. *Bq25570 datasheet*. 2021. Online; accessed 2021-02-10. Available from Internet: ⟨https://www.ti.com/lit/ds/symlink/bq25570.pdf⟩. Cited on page 30.

JIANG, X.; POLASTRE, J.; CULLER, D. Perpetual environmentally powered sensor networks. In: *IPSN 2005. Fourth International Symposium on Information Processing in Sensor Networks, 2005.* [S.l.: s.n.], 2005. p. 463–468. Cited on page 18.

KJELLBY, R. A.; JOHNSRUD, T. E.; LOETVEIT, S. E.; CENKERAMADDI, L. R.; HAMID, M.; BEFERULL-LOZANO, B. Self-powered iot device for indoor applications. In: *2018 31st International Conference on VLSI Design and 2018 17th International Conference on Embedded Systems (VLSID)*. [S.l.: s.n.], 2018. p. 455–456. Cited 2 times on pages 18 e 23.

LTDA, V. A. S. de A. *Vitau Automation Website*. 2021. Online; accessed 2022-02-10. Available from Internet: ⟨http://www.vitauautomation.com⟩. Cited on page 37.

MANWARING, K.; CLARKE, R. Surfing the third wave of computing: A framework for research into eobjects. *Computer Law Security Review: The International Journal of Technology Law and Practice*, v. 31, p. 586, 08 2015. Cited on page 16.

MONOLITHIC, A. *AMS1117 datasheet*. 2021. Online; accessed 2020-12-10. Available from Internet: ⟨http://www.advanced-monolithic.com/pdf/ds1117.pdf⟩. Cited on page 37.

NREL. *Best Research-Cell Efficiency Chart*. 2021. Online; accessed 2022-03-24. Available from Internet: ⟨https://www.nrel.gov/pv/cell-efficiency.html⟩. Cited on page 25.

PETER, C.; PHILIP, V.; PAVAN, S.; TIM, W.; LESLIE, O. Long-duration solar-powered wireless sensor networks. In: . [S.l.: s.n.], 2007. p. 33–37. Cited on page 18.

POLASTRE; SZEWCZYK; CULLER. Telos: enabling ultra-low power wireless research. In: *IPSN 2005. Fourth International Symposium on Information Processing in Sensor Networks, 2005*. [S.l.: s.n.], 2005. p. 364–369. Cited on page 18.

ROHM, S. *BH1750 datasheet*. 2021. Online; accessed 2020-04-05. Available from Internet: ⟨https://www.mouser.com/datasheet/2/348/bh1750fvi-e-186247.pdf⟩. Cited on page 22.

RUFER, A. *Energy Storage - Systems and Components*. [S.l.]: Boca Raton: CRC Press, 2018. 53–97 p. Cited on page 32.

SNIJDERS, F. Ambient intelligence technology: An overview. In: ______. *Ambient intelligence*. First. [S.l.]: Springer, 2005. Cited 3 times on pages 16, 31 e 32.

SYEDA, A. A.; ALMUSAWI, H.; GéZA, H. Towards the self-powered internet of things (iot) by energy harvesting: Trends and technologies for green iot. In: *2018 2nd International Symposium on Small-scale Intelligent Manufacturing Systems (SIMS)*. [S.l.: s.n.], 2018. p. 1–5. Cited on page 18.

SYSTEMS, S. E. *ESP32 WROOM datasheet*. 2021. Online; accessed 2020-04-05. Available from Internet: ⟨https://www.espressif.com/sites/default/files/documentation/esp32-wroom-32datasheeten.pdf⟩. Cited 2 times on pages 20 e 21.

TEXAS, I. *INA219 datasheet*. 2021. Online; accessed 2021-03-15. Available from Internet: ⟨https://www.ti.com/lit/ds/symlink/ina219.pdf⟩. Cited on page 23.

THAKUR, S.; PRASAD, D.; VERMA, A. Energy harvesting methods in wireless sensor network: A review. *International Journal of Computer Applications*, v. 165, p. 19–22, 05 2017. Cited on page 23.

WAGIH, M.; WEDDELL, A. S.; BEEBY, S. Rectennas for radio-frequency energy harvesting and wireless power transfer: A review of antenna design [antenna applications corner]. *IEEE Antennas and Propagation Magazine*, v. 62, n. 5, p. 95–107, 2020. Cited on page 28.

WERNER, W.; RABAEY, J. M.; AARTS, E. H. L. *Ambient intelligence*. First. [S.l.]: Springer, 2005. Cited 2 times on pages 16 e 40.