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Energy Harvesting IoT devices

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Abstract

The rapid expansion of the Internet of Things (IoT) has sparked significant interest in the development of low-power wireless sensors, now essential components of loT systems. These sensors are seamlessly integrated into various sectors, including transportation, energy management, infrastructure, smart buildings, environmental monitoring, healthcare, defence, manufacturing, and production. Ensuring the long-term sustainability of lot devices is crucial from the outset of design and implementation. Traditionally, wireless sensors have relied on batteries for power, despite their cost-effectiveness. However, battery reliance can lead to limitations such as shortened lifespan and compromised network performance. Energy Harvesting (EH) technology emerges as a promising, environmentally friendly alternative. EH not only extends sensor lifespans but also has the potential to entirely replace battery power in certain cases. Additionally, EH offers economic and practical advantages by optimizing energy utilization and reducing network maintenance costs. This review examines recent advancements in energy harvesting techniques tailored for lot applications. Through case studies, two EH techniques are demonstrated to illustrate their effectiveness. However, significant research challenges remain to enable the widespread deployment of energy harvesting solutions in loT environments. These challenges include enhancing energy conversion efficiency, seamless integration of EH with lot systems, and adaptation of EH technology to diverse application scenarios. Overcoming these hurdles holds the promise of revolutionizing the sustainability and efficiency of lot deployments across various sectors.

1. INTRODUCTION:

The International Telecommunications Union (ITU) released its inaugural report on the Internet of Things (IoT) years ago [1]. The IoT paradigm was initially conceptualized as an expansion of Information and Communication Technologies (ICTs), enabling universal connections between individuals and objects, unrestricted by time or location, thus forming a dynamic network of networks [1]. Today, IoT has transcended its status as an emerging trend to become one of the most vital technologies of the current century. It finds application across numerous industries, including transportation, energy, civil infrastructure, smart buildings, environmental monitoring, healthcare, defence, manufacturing, and production. The expansion of IoT is ongoing, with experts forecasting that by 2025, approximately 22 billion IoT devices will be interconnected, communicating within this IoT ecosystem [2].

The IoT ecosystem has the following main component [3]:

- IoT devices (sensors and actuators) collect data or control processes.
- IoT connectivity (protocols, gateways) transfers data in the online, cyber-physical realm.
- The IoT cloud stores data and serves as the decision-making hub.
- IoT analytics and data management process the data.
- End-user devices and interfaces aid in system control and configuration.

Each component must tackle significant scientific and technological hurdles to achieve efficient and scalable implementations. For instance, energy efficiency is a crucial consideration during the design phase of IoT devices [4]. Facilitating a seamless flow of information within the IoT ecosystem poses another significant challenge, given the complexity of wireless connectivity and the rapid evolution of wireless standards. Developing new Artificial Intelligence (AI) techniques capable of analyzing vast amounts of data and making real-time decisions presents another major hurdle. Additionally, security and privacy considerations are paramount, as existing security protocols like Data Encryption Standard (DES), Advanced Encryption Standard (AES), and Rivest, Shamir, and Adelman (RSA) are unsuitable for IoT devices due to their resource constraints and heterogeneity [5-7].
Below, we outline the challenge related to the energy efficiency paradigm for certain IoT devices, particularly wireless sensors. The IoT vision leverages the capabilities of Wireless Sensor Networks (WSNs) [8, 9] and IoT relies on these systems to gather environmental data and execute actions based on data analysis. While IoT employs Internet Protocol (IP) connectivity to assign distinct addresses to each component or "thing," Wireless Sensor Networks (WSNs) do not always need an internet connection. However, with the continuous advancement of microelectronics, accompanied by decreasing costs and enhanced power efficiency of hardware technologies and wireless communication protocols, WSNs have evolved into a crucial element of the IoT ecosystem. WSNs have the capability to extend the Internet or the cyber environment into physical spaces [4, 10]. Moreover, IoT and WSN have become almost inseparable [11], wireless sensor networks being recognized as a key enabler of IoT [12]. Some of the domains, wherein IoT technologies have been integrated with WSNs include healthcare [13], agriculture [14], smart cities [15] and smart buildings [16], manufacturing [17], and transportation systems [18]. Figure 1 shows a typical IoT scenario where data also is collected using WSNs.

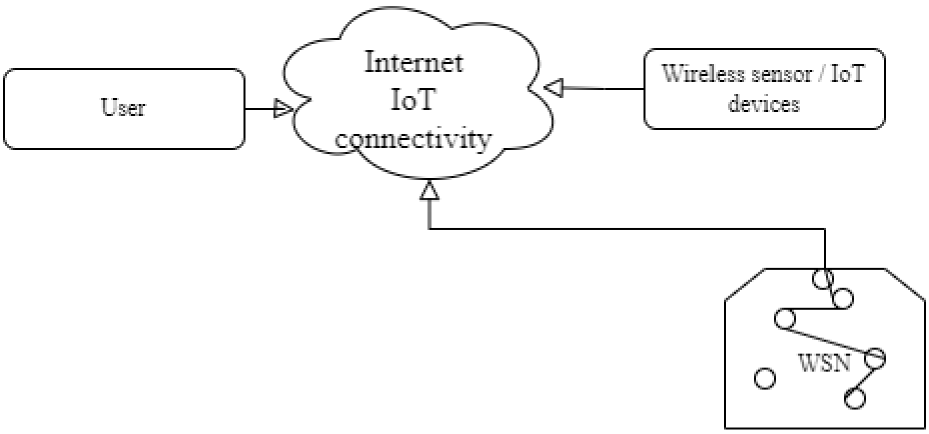


FIGURE 1. Wireless Sensor Networks (WSNs)

Wireless sensor networks offer significant advantages in applications where access is challenging, such as remote locations or on mobile machinery components[19-22]. Typically, a wireless sensor comprises four primary components: the sensorial part, processor, transceiver, and power supply, as illustrated in Figure 2 [23]. Wireless sensors typically face constraints in processing power, storage, and energy availability due to reliance on batteries with limited capacity.

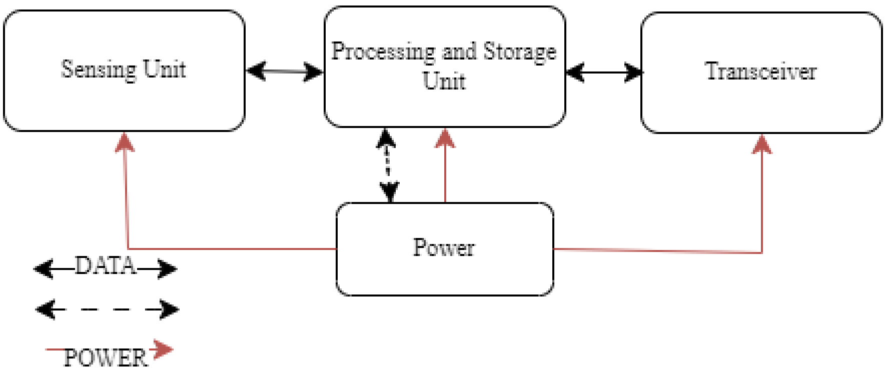


FIGURE 2. Wireless sensor (IoT device) components

Additionally, challenges in deploying solutions using wireless sensors include ensuring reliable communication, addressing coverage and deployment issues, enhancing security measures, ensuring Quality of Service (QoS) assurance, and efficiently managing large volumes of data [10]. Hence, ensuring the long-term and self-sustainable operation of wireless sensors (IoT devices) is paramount and requires proper attention. Energy Harvesting (EH) technology emerges as an eco-friendly solution with the potential to prolong the lifespan of these sensors. Energy harvesting involves capturing energy from diverse external sources and converting it into electricity.

This study focuses on analyzing energy harvesting techniques applicable to IoT devices. We summarize our research contributions as follows:

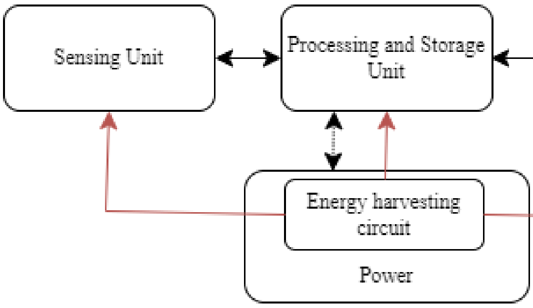
- We provide motivation for the importance of energy harvesting in the IoT ecosystem.
- Through a thorough review of energy harvesting solutions for IoT, we examine various techniques for harvesting energy from diverse sources.
- We introduce two IoT energy harvesting devices developed by the authors, detailing considerations regarding their design, implementation, and testing.

The article is structured to provide a comprehensive exploration of energy harvesting in IoT. It begins with a focus on the significance of energy harvesting by highlighting the limitations of relying on batteries for wireless sensors. Following this, an overview of energy harvesting techniques is presented, including a classification based on energy sources and an analysis of recent advancements. The subsequent section delves into energy harvesting models and consumption models proposed for IoT devices. Two case studies on solar and RF energy harvesting are then discussed, detailing the architecture, operation, and energy characteristics of relevant IoT devices. Additionally, a prototype for a BLE-enabled environmental beacon powered by RF energy harvesting is introduced. The article further addresses technical challenges in energy harvesting device design and development, despite recent progress in self-powered IoT devices. Concluding remarks summarize key findings and highlight future directions in the field.

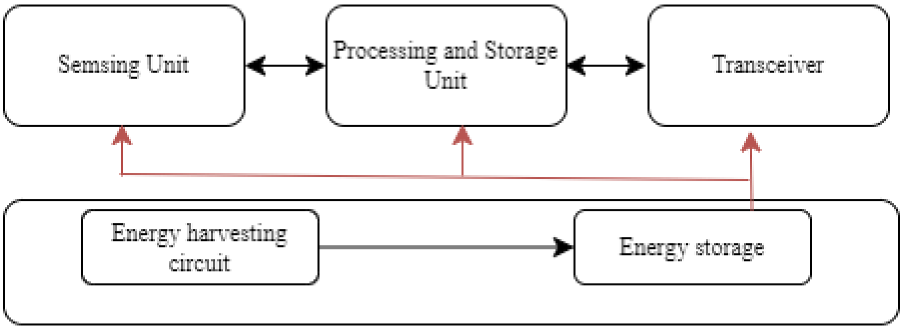
1.1 MOTIVATION FOR ENERGY HARVESTING IN IOT:

Maximizing the network lifetime is paramount in the design and development of wireless sensors (IoT devices), necessitating a focus on energy efficiency and prolonged battery lifespan. Despite notable advancements in communication protocols, operating systems, and robust power management mechanisms, the finite capacity of batteries poses a challenge. Eventually, batteries will deplete, requiring costly maintenance operations such as replacements to sustain network operation. Moreover, the extensive scale of wireless sensor networks, combined with sensor deployment in remote or inaccessible locations, compounds the difficulty of these maintenance tasks. Consequently, there is a pressing need for alternative solutions like energy harvesting to alleviate reliance on finite battery capacities and mitigate the logistical challenges associated with maintenance operations, thus extending the network's operational lifespan [24]. Utilizing batteries as the power source for wireless devices comes with additional drawbacks beyond their finite lifespan. These include reduced energy densities and leakage, resulting in battery discharge even during periods of non-use. Furthermore, the application range of batteries is constrained by temperature sensitivity, with extreme conditions causing capacity and power losses, thereby limiting their effectiveness [25]. Another problem, that is common to the operation of wireless sensors is the proper management of short high-current pulses that affect the capacity and lifetime of batteries [26]. Battery weight and dimensions directly affect capacity, and their reduction for achieving small form factor designs will lead to a shorter operation time for the devices they power. Another major concern is related to the environment because batteries contain harmful chemicals and toxins that make their disposals more complex [25, 27] . Although most batteries can be recycled and many governmental initiatives have been established for increasing the recycling rates, improvements in this direction are still necessary [28]. Presently, there is a widespread movement aimed at minimizing the environmental footprint of Information and Communication Technology (ICT), which extends to wireless sensors. The objective is to develop sustainable and energy-efficient systems, aligning with broader environmental conservation efforts [29]. These factors underscore why energy harvesting elements are integrated into the design of contemporary wireless sensors. These components serve as supplementary power sources or can even replace traditional batteries entirely. Energy harvesting prolongs the lifespan of wireless sensors by replenishing their energy reserves from various sources, such as solar cells, vibrations, fuel cells, ambient acoustic noise, or mobile suppliers like robots [10]. Incorporating energy harvesting ensures the long-term and self-sustainable operation of wireless sensors, addressing one of the critical challenges in the extensive adoption of IoT [29].

Energy harvesting, also known as energy scavenging, is the process of capturing and converting energy from external sources, such as mechanical loads, vibrations, temperature gradients, or light, into usable electrical power. This harvested energy is typically in relatively small levels but can be utilized to supply power to electronic devices [4, 30]. The acquisition of energy from the surrounding environment results in a green energy source that can replace primary batteries or charge secondary cells. This approach represents a cost-effective and environmentally sustainable method for powering wireless devices [31]. The three components of a common energy harvesting system are the source (external energy that is collected), the harvesting architecture (mechanisms), and the load (the consumer) [32]. The energy can be used immediately at the time it is harvested or it can be stored for future use, resulting in two main architectures, namely, Harvest-Use and HarvestStore-Use [32]. Figure 3 depicts two distinct architectures for a wireless sensor node outfitted with energy harvesting elements. These architectures dictate the configuration of the system, with each having its specific power generation component comprising dedicated energy harvesting circuits responsible for converting ambient energy into Direct Current (DC) energy. Additionally, power management units are integrated to optimize the efficiency of power generation and utilization. The system also features storage elements designed to store energy for powering the electronics. Intensive research efforts are directed towards these components, their associated characteristics, and functions, with the goal of producing energy-autonomous wireless sensors suitable for deployment in IoT environments.



(a) Wireless sensor (IoT device) with energy harvesting architectures: Harvest-Use. Adapted from [32]



(b) Wireless sensor (IoT device) with energy harvesting architectures: Harvest-Store-Use. Adapted from [32]

FIGURE 3

2. ENERGY HARVESTING TECHNIQUES FOR IOT:

Energy harvesting presents various sources, categorized into ambient, mechanical, human, organic, and hybrid types. Ambient sources, easily accessible in the environment at no cost, include solar, Radio Frequency (RF), thermal, wind, and hydro energy sources. Solar energy, from sunlight, pairs with RF energy from wireless signals, thermal energy from temperature changes, wind energy from air currents, and hydro energy from flowing water. Mechanical sources, like vibrations and pressure, are deliberately placed for energy collection. Human activity, such as motion and physiology, contributes to harvesting, as do energy sources from organisms and plants. When one source isn't sufficient, a hybrid approach combines these for robust power generation[24]. Vibrations and pressure are mechanical energy sources that are deployed explicitly in the environment for harvesting purposes [24]. Humans through their motion and physiology, organisms, and plants, represent other sources of energy that can be scavenged. In some cases, the use of only one energy source is not enough, therefore several types of energy sources must be combined to reap sufficient power needed by electronic equipment.

2.1 AMBIENT ENERGY HARVESTING

In the realm of self-powered devices for the IoT ecosystem, solar and RF stand out as the primary ambient energy sources, consistently available in the environment either naturally or through artificial means. Due to their ubiquitous nature, these sources are particularly suitable for consideration. As such, this work narrows its focus exclusively to these ambient sources: solar and RF. By honing in on these reliable and omnipresent energy sources, the aim is to develop efficient self-powered devices tailored for the IoT ecosystem.

2.1.1 SOLAR ENERGY HARVESTING

Solar power stands as Earth's most abundant energy source, continuously producing approximately 173 × 1012 kW of energy. This immense quantity far surpasses the world's demand and usage, highlighting the vast potential of solar energy as a renewable and plentiful resource[33]. Annually, the total energy that reaches the Earth's surface amounts to approximately 3.4 × 1024 joules. This staggering quantity is 7000 to 8000 times greater than the globe's yearly primary energy consumption. This comparison underscores the immense abundance of energy available from the sun, emphasizing its potential to fulfill global energy needs many times over[34]. The energy from the sun is harvested through various methods, including helio-chemical processes such as photosynthesis, helio-electrical processes like photovoltaic converters, and helio-thermal techniques such as thermal energy production and solar water heaters. These diverse approaches to harnessing solar energy allow for its conversion into usable forms, supporting a range of applications from electricity generation to heating systems[35]. The helio-electrical process relies on the PhotoVoltaic (PV) effect, which becomes evident when two dissimilar materials convert solar rays into DC (direct current) power upon exposure to light. This phenomenon enables the generation of electricity from sunlight by utilizing materials that exhibit the PV effect, making photovoltaic systems a key technology in solar energy conversion[24]. The solar cell, or photovoltaic cell, is the key device for generating electricity from sunlight. This solid-state electrical junction converts sunlight into electricity through the photovoltaic effect. When sunlight strikes the cell's semiconductor material, it produces an electric current, enabling the generation of usable electrical power[24]. Typically made from silicon, solar cells use a manufacturing process similar to transistors and Integrated Circuits (ICs)[34]. The main types of PV cells, depending on the materials in their composition, are the mono-crystalline, polycrystalline, and amorphous silicon, or thin-film cells [34, 36]. Efficiency, the key performance metric, is the ratio of a solar cell's maximum output power to incident light power under 100 mW/cm² illumination[37]. In the first category, mono-crystalline PV cells boast the highest efficiency, ranging from 15 to 24%. However, they are also the most costly. Polycrystalline PV cells, in the second group, offer efficiencies between 14 and 20%. Thin-film cells are the least expensive but have efficiencies below 13.2% [36].

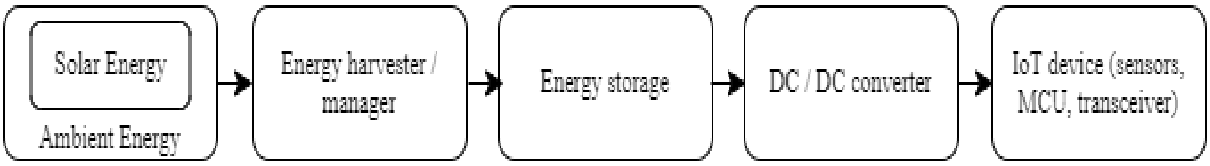


FIGURE 4: Main components of a solar energy harvesting system.

In wireless sensors, solar cells are a well-established method for energy harvesting, commonly employed to extend the lifespan of power supplies[38 - 40]. Solar cells present the highest power density, around 15 mW/cm², surpassing other energy harvesting techniques in efficiency [41]. Solar power, while uncontrollable and affected by day-night cycles, seasonal shifts, weather, and temperature, can be predicted and modeled. These forecasts allow for strategies ensuring continuous power supply to electronic devices [42- 46]. To ensure continuous operation of solar-powered devices, especially during periods without ambient light like night or cloudy weather, a common architecture includes storage elements, as depicted in the Figure [47, 48]. Energy storage options for solar-powered devices include rechargeable batteries, supercapacitors, or a combination of both, each with unique advantages and limitations. Excess energy is stored when generation surpasses device consumption or during sleep mode.

This stored power is then utilized when the energy source is unavailable or needed by the system [48]. PV cells, a well-established technology, have found applications in a broad spectrum of IoT devices. When paired with proper energy storage, power consumption optimization, and precise circuit design, PV technology enables the development of efficient, energy-autonomous devices [49 - 53]. Initially intended for outdoor use, energy harvesting with PV technology primarily focuses on generating energy from sunlight. PV cells are designed with higher conversion efficiencies for outdoor environments, while their efficiency in indoor settings tends to be lower due to reduced light availability [54, 55]. However, advances in manufacturing processes and circuits along with improved designs of IoT devices have enabled the deployment of indoor solar powered systems [56 - 59].

Substantial advancements have been achieved in energy supplies for moderate power systems, typically consuming 1 to 10 watts. This progress aligns well with the prevalent use of low-power IoT devices, which typically require between 10 and 100 milliwatts of power [60]. This allows energy autonomous embedded systems to run data-intensive tasks such as computer vision and facilitates the implementation of edge computing technologies.

2.1.2 RF ENERGY HARVESTING

Wireless Internet, radio, satellite stations, and digital multimedia broadcasts emit RF or electromagnetic signals within the frequency spectrum of 3 kHz to 300 GHz. These signals can be converted into electrical energy using an antenna and rectifier circuit, as depicted in Figure 5. RF energy, present indoors and outdoors, is continuously available day and night. Although abundant and limitless, it has drawbacks such as low density and efficiency, which decreases with distance [61]. Based on a review of the past literature in this area [61 – 63], we found that RF waves energy harvesting is the best solution in many scenarios when it comes to low-energy IoT devices. The works in [64, 65] and [66] highlight the potential of using RF Energy Harvesters (RFEHs) to power IoT devices for environmental and healthcare monitoring. Other approaches for harvesting energy from RF signals include opportunistic charging from nearby smartphones [67], or the sharing of energy between different wireless systems close to each other [68].

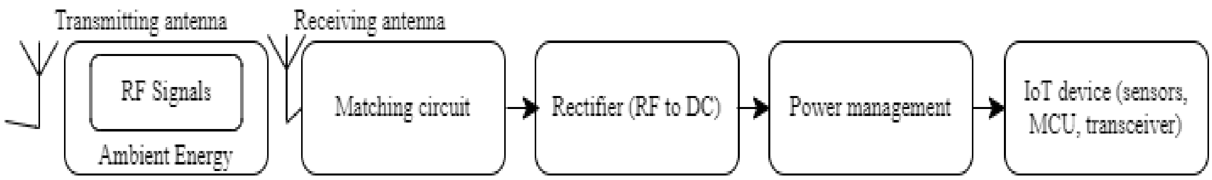


FIGURE 5: Main components of a RF energy harvesting system

2.2 MECHANICAL ENERGY HARVESTING

Mechanical vibrations and pressure are energy sources that surround us, and these sources can be considered in making self-powered IoT devices used in a wide range of applications.

2.2.1 MECHANICAL VIBRATIONS ENERGY HARVESTING

Mechanical vibrations have a sufficiently high energy density and, in some cases, where IoT devices are deployed indoors or in overcast areas, their use can replace solar harvesting systems. The energy from low frequency (< 100 Hz) or high frequency (> 100 Hz) vibrations is usually harvested through piezoelectric, triboelectric, electromagnetic, and electrostatic energy harvesters.

The Piezoelectric Energy Harvesters (PEHs) work based on the combination between the mechanical and the electrical behaviors of certain categories of materials such as crystals and ceramics [69]. These

harvesters do not require external voltage sources, have a minimum of moving parts, and can generate power with voltage levels that can be easily conditioned (i.e., converted to DC) [70]. This type of harvesters benefits from high-power density, simplicity in their design and fabrication, and they use a wide range of frequencies. Based on the literature review in this area, we found that the piezoelectric energy harvesting is the most widely researched. The works in [70 – 74] analyze state-of-the-art of energy harvesting using piezoelectric generators at micro and nano scale and highlight that this method is one of the most promising solutions to power IoT devices. In [75], the authors used PEHs installed on an actual roadway for five months, with vehicles traveling at speeds of 10–50 km/h. The maximum generated power of 2080 mW and a power density of 20.79 W/m2 were recorded with a vehicle speed of 30 km/h, and 2381 mW and a power density of 23.81 W/m2 at a vehicular speed of 50 km/h. Another test presented in [75] involved the use of eight PEHs installed on the highway rest area. The results obtained prove the harvesters' ability to successfully operate 24 LED indicators that can ensure drivers' safety at night, to monitor in real time the conditions inside the harvesters through their sensors (temperature, strain, and leakage), and to collect traffic data such as the number of vehicles passing the harvester zone.
The ElectroMagnetic Energy Harvesters (EMEHs) work based on the relative motion between a conductor (such as a coil) and a magnetic field (created by a magnet) in response to mechanical vibrations. This category of harvesters has attracted considerable attention due to their ability to generate high output currents, robustness, and their low-cost designs. However, they continue to be challenging in terms of poor transduction properties of planar magnets and the limited number of induction loops when it comes to IoT small-scale devices [69].
In [76], the authors proposed a battery-free solution to power a Bluetooth board with a DC voltage equal to 2 V by a low voltage vibration electromagnetic converter (with an open circuit output voltage equal to 1.8 V peak to peak for a frequency of 24 Hz) as energy source. In [77], the authors present an EMEH working at low frequency ambient vibrations (< 100Hz). To demonstrate the design, a macro level prototype was used, and the voltage generated for a frequency of 50 Hz and 20 turns of copper coil is 20 mV, i.e., 1mV per turn. The approach described in [78] presents a viable hybrid solution which includes an EMEH to collect the energy from the bridge's vibrations and ambient wind surges to implement IoT devices for bridges' health monitoring. Two prototypes with multi-resonant frequencies have been designed. The first prototype, suitable for narrow band vibration environments, has a frequency band from 1 to 18 Hz and acceleration levels below 0.4 g and generates an open circuit voltage of 810 mV and an optimum power of 354.51 µW. It also produces an adequate voltage and power levels (up to 7.84 µW) from wind surges from 0.5 m/s to 9 m/s. The second prototype, suitable for vibration surroundings, has a frequency band from 1 to 45 Hz and acceleration levels below 0.6 g and generates an open circuit voltage of 618 mV and an optimum load power of 2214.32 µW. It can harvest the power (up to 9.14 µW) from ambient wind with speed from 0.5 m/s to 6 m/s.
The ElectroStatic Energy Harvesters (ESEHs) use the mechanical vibrations to move the charged capacitor plates of a variable capacitor structure against the electrostatic forces between the electrodes which are separated by air, vacuum, or a dielectric material [69]. Unlike PEHs and EMEHs, ESEHs require a DC voltage (bias voltage) supplied by a battery to oppositely charge the capacitor plates. ESEHs generate high output voltage and relatively larger output power density, provide a wider choice of frequencies at the low-frequency range, and offer the possibility to build low-cost devices. In [79] the authors present an ESEH (whose footprint is as small as 1 cm2) that can reach an output power of 495 µW sinusoidal vibration. Used in real life conditions, under impact vibration inside of a tire tread, the harvester generates an output

power of 60 µW on a traveling speed of 60 km/h. The result of the research contributes to the evolution of intelligent automobiles in terms of tire sensors (IoT devices). The work presented in [80] proposes an ESEH design based on the electrostatic coupling methods. The results demonstrate that the ESEH can harvest more than 1 µW from 59 to 148 Hz, and more than 0.5 µW from 14 to 152 Hz at an acceleration of 2 grms (Root Mean Square acceleration). It was successfully used to power an energy autonomous temperature sensor node with a data transmission beyond a distance of 10 m at 868 MHz.

2.2.2 MECHANICAL PRESSURE ENERGY HARVESTING

Mechanical pressure is exploited to implement energy harvesters using the piezoelectric method, but to a lesser extent than vibrations. For example, the work in article [81] demonstrates the feasibility of using this energy source.

2.3 HUMAN ENERGY HARVESTING

The human body is an energy warehouse which can ensure alterative power supply through the collection of energy from heat and motion [82]. This type of energy source can be exploited by wearable and implantable electronic devices that are IoT devices used to monitor the activity of healthy people or the patient's condition. However, this energy harvesting approach encounters difficulties due to the following factors: human motion has a relatively low frequency (typically under several tens of Hz) and also it is highly stochastic and irregular; the human body temperature depends on the daytime rhythm and on the instant disturbance of daily activities performed [82]. Additionally, the devices must be worn by people and therefore they must have reasonable size and weight and must interfere only minimally with the natural functions of the body [83].

The research conducted in this field has focused on the extraction of energy from human body focusing on heat [84 – 91] and biomechanical energy [83], [92 – 96].

2.3.1 HUMAN HEAT ENERGY HARVESTING

Human heat energy harvesting is based on the changes of the human body temperature and uses two types of energy harvesters: the ThermoElectric Energy Harvester (TEEH) that utilizes a spatial-temperature gradient and the PyroElectric Energy Harvester (PEEH) which requires a temporal variation in temperature. The work [84] presents an ultra-low power batteryless energy harvesting Body Sensor Node (BSN) capable of acquiring, processing, and transmitting ElectroCardioGram (ECG), ElectroMyoGram (EMG), and ElectroEncephaloGram (EEG) data. The BSN is totally powered by a commercially available TEEH with about 60 µW output power with 30 mV output voltage. In the heart-rate extraction mode where the transmitter is dutycycled, the sensor node, including regulation, consumes only 19 µW. The authors of [85] describes a hidden TEEH of human body heat, integrated into an office shirt. It generates power in the range of 5-0.5 mW at ambient temperatures of 15 ◦C to 27 ◦C. The tests made highlight that the thermoelectric shirt produces more energy during nine months of use (if worn 10 h/day) than the energy stored in alkaline batteries of the same thickness and weight. Its technical properties make it a reliable power supply for low-power IoT devices used in healthcare. More information on TEEHs for human heat energy harvesting is provided in [86 – 88]. The temperature variations of the human body are not high during the day. In this condition, the available heat energy for PEEHs is limited. This is why when it comes to human body energy harvesting applications, PEEHs are combined with other types of energy harvesters. Such an approach is demonstrated in [89] through a proof of concept of a hybrid harvester combining piezoelectric and pyroelectric properties for building self-powered healthy monitoring and interactive sensing systems. The tests made to determine the output voltage and current from the pyroelectric effect, in the absence of any strain, by varying the temperature of the hot plate to which the sensor is attached from 295 K to 303 K, yielded an output voltage and current pulse peaks up to 0.1 V and 20 nA respectively. These correspond to a peak power density of 2 mW / cm−3 . Also, the approaches [90, 91] present viable hybrid solutions which include PEEHs to implement wearable IoT devices.

3.2.2 BIOMECHANICAL ENERGY HARVESTING

Biomechanical energy available from human motion can be classified into kinetic energy and elastic energy [82]. Given the complexity of the physical mechanisms, several types of energy harvesting devices are used: electromagnetic, electrostatic, piezoelectric, and triboelectric [82], [92]. Based on our review of the literature [82], [92 – 94] in this area, we found that a wide range of devices and applications have been reported. These published studies show that in terms of power generation, the electromagnetic energy harvesters are the best candidate to capture the kinetic energy. However, the benefit that the IoT devices based on smart material-based energy harvesters offer to those who wear them cannot be ignored. The authors of [95] described an electromagnetic energy harvester prototype to efficiently scavenge the kinetic energy of human limbs swing. In real walking conditions, the maximum power achieved was 1.84 mW and 2.95 mW for the device worn on the wrist and ankle respectively, while the corresponding power densities are 573.21 µW / cm3 and 919.01 µW / cm3 , respectively. The results confirm that the energy harvester can entirely power a pedometer at various walking speeds. The work in [96] presents the design, implementation, and evaluation of a fiber-based generator that converts biomechanical energy (motions/vibrations) into electricity using electrostatic mechanisms. The average output power density of ~0.1 µW / cm2 makes this generator usable as an effective building element for a power shirt to trigger a wireless body temperature sensor system and as a self-powered active sensor to quantitatively detect human motion.

2.4 BIOENERGY HARVESTING

Specialized forms of energy harvesting also exist, such as using plants to generate energy for powering wireless sensors. This innovative approach has been a subject of investigation [97]. The plant-as-battery approach is meant to simplify the deployment of wireless sensors in agricultural applications, where the measurement of soil moisture, ambient humidity, or the monitoring of plants for detecting pests are some of their common functions. The authors of [97] describe an approach that exploits the ability of plants to produce electric signals that are harvested by a power management unit, generating a power between 800 and 1400 nW during a day. This energy is sufficient for transmitting an electric signal with a single switch using low power bistatic scatter radio principles. The use of soil energy for powering wireless sensors has been proposed in [98], where the temperature and air moisture are measured and transmitted using BLE technology to terminal devices such as smartphones. The soil cell fabricated by the authors supplies an average power of 60 to 100 µW which is sufficient to power the BLE sensor so that it can perform the aforementioned tasks. These approaches can help in the development of environmentally friendly monitoring applications in IoT contexts.

2.5 HYBRID ENERGY HARVESTING

In some scenarios, harvesting energy from a single source may not generate sufficient power for continuous operation of IoT devices. To address this challenge, systems have been designed with multiple energy harvesting units, complemented by energy storage components [99]. An example of this is solar energy harvesting, where converting light into DC power can provide the necessary energy for wireless sensor nodes. However, the main drawback of solar energy is its reliability, influenced by weather conditions and spatial-temporal factors like the Sun's position throughout the day [41]. Therefore, hybrid solutions, where solar energy harvesting is complemented by other mechanisms or power supplies have been proposed [41, 48, 99]. Hybrid energy harvesters combine circuits that generate power from single energy sources, such as solar, radio frequency, and vibrations and can also use multiple types of transduction mechanisms for converting energy to electricity [100]. By generating a power output equal to, or larger than the overall consumption of an IoT device for a certain period, energy-autonomy is achieved. In [101], the authors presented the design, implementation, and evaluation of a self-powered WSN node with wind, solar, and thermal energy. The average generated capacity by the harvesting mechanisms of 7805.09 J exceeds the energy consumption of the node, measured at approximately 2972 J, demonstrating the practicality of the hybrid approach.

Table 1 presents a summary of this section. It describes each energy source along with the technology used to harvest it, the advantages and disadvantages of these technologies, the range of power density obtained, and the application domains that can get benefit if they use them to develop self-powered IoT devices.

3. ENERGY HARVESTING MODELING

The preceding section outlined key energy sources and harvesting technologies for developing IoT devices. Regardless of the technology employed, in the design phase of IoT devices with energy harvesting capabilities, it is crucial to maintain a balance between generated and stored power and the power consumed.

In this context, two main approaches have been proposed: Harvest-Store-Use and Harvest-Use (less common and unsuitable for uncontrollable or unpredictable energy sources). Energy harvesting models under the Harvest-Store-Use approach consider the storage element's capacity, where harvested energy can either always be stored or up to a limit, with the excess lost. This harvested energy can be modeled deterministically or stochastically. Deterministic models are apt for predictable energy sources with known fluctuations, while stochastic models suit unpredictable sources. However, in both cases, the core idea is to harvest enough energy for IoT devices' operation without a battery. Typically, the power source should support data processing, transmission, receiving actions, and sleep periods. Figure 6 illustrates this with a supercapacitor voltage chart charged by a solar cell, powering a temperature and humidity sensor. These sensors periodically send data to a cloud platform via the Internet. The graph depicts a positive scenario where the solar cell adequately charges the storage element for autonomous operation.

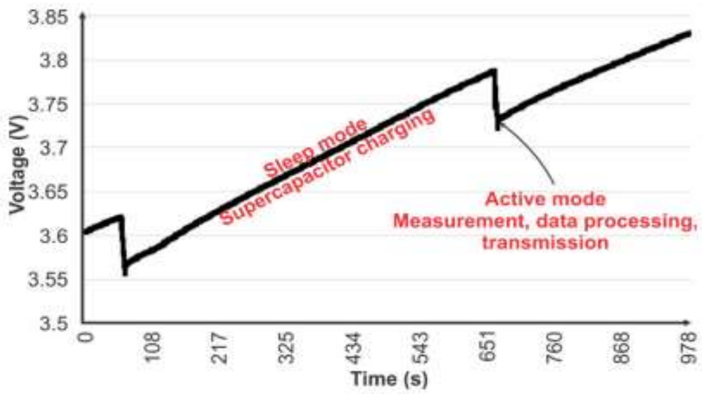


FIGURE 6: Voltage on the storage element (supercapacitor) during operation – T and RH Wi-Fi sensor

As we have previously mentioned, although energy harvesting poses many challenges, the majority of these can be overcome by efficient, energy aware, system designs [103]. Since the amount of scavenged energy is so low (as Table 1 shows), in most cases the energy harvesting IoT device must operate on amounts of power as low as possible. Several strategies have been proposed for prolonging the lifetime of wireless IoT devices, including duty-cycling [104], sleep scheduling [105], the reduction of the required transmission distance for IoT devices through efficient clustering [106], optimized strategies for adaptively setting the rates of sensor reading and data transmission depending on available energy [56], or the development of scheduling schemes that take into account power consumption when waking up the wireless sensing systems [107]. Some practical techniques for reducing the energy required by an IoT device, also used in the development of low-power embedded systems, include Dynamic Voltage Scaling (DVS) [108], the reduction of the frequency of the processing unit [109], or the appropriate selection of peripherals in the device [110] or of the type of memory involved in data processing and storage (i.e., Flash or RAM -- Random access memory) [111], the adaptation of transmission power depending on required communication range and environment [112, 113], or logic for deciding the moment and format for sending slow varying data [114 – 116]. All these approaches for assuring lowpower operation must be scheduled and further modified depending also on the amount of energy that is generated or stored by the IoT device at each moment in time [50]. Since in most cases of wireless IoT devices, communication is the most expensive operation from an energy perspective [117], many of the research efforts focus on efficient communication protocols [117 – 121] and on the optimization of the transmission, through careful planning and simple data exchanges [114, 122, 123]. However, with the development of extremely low-power communication technologies, such as BLE [124], and the inclusion in the design of IoT devices of many sensors, some of them with special requirements regarding timing and energy supply, such as gas sensors, it is possible that sensing and data processing consume the most energy in their design [4, 125]. In these cases, algorithms for determining the optimal time for sensor sampling, considering the amount of energy scavenged and stored, must be developed for assuring energy autonomy in the case of energy harvesting IoT devices [50].

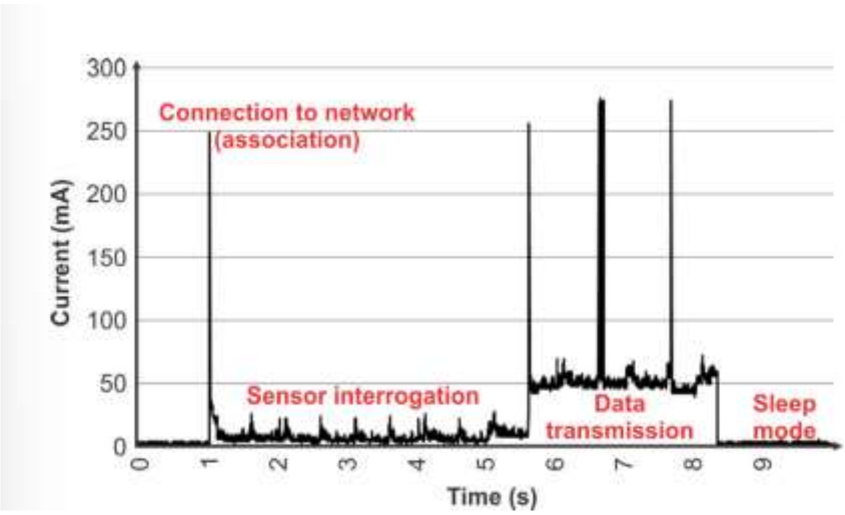


FIGURE 7: Profile of the current drawn by a Wi-Fi sensor during wakeup (T, RH, P, CO2, and light intensity)

The calculation of the energy budget required by the IoT device during operation is also of great importance in the selection of a proper power source. The energy profile [104] of the IoT device can be used for estimating the amount of power required for its proper operation. Figure 7 presents the power signature of an IoT device that measures the temperature, relative humidity, carbon dioxide level, absolute pressure, and light intensity, and sends the data to a predefined IP address using Wi-Fi connectivity and the User Datagram Protocol (UDP) protocol [126]. By knowing the amount of energy consumed during all the activities performed by the device and their duration, the average energy required by the system can be computed. This estimation can then be used for choosing strategies for optimizations (i.e., modifying the sleep / wakeup ratio, sampling sensors with different rates, etc.) and for properly designing the energy harvesting elements.

Energy Harvesting Technique	**Advantages**	**Disadvantages**	**Power Density Range**	**Application Domains**
Solar	Abundant, renewable	Reliability on sunlight, weather-dependent	15 mW/cm²	Outdoor sensors, weather monitoring
RF (Radio Frequency)	Ubiquitous, continuous	Low density, efficiency with distance	-	Wireless communication, remote sensing
Thermal	Harvests waste heat	Low efficiency, temperature-dependence	-	Industrial monitoring, waste heat recovery
Mechanical	Converts vibrations to electricity	Limited by available vibrations	-	Structural health monitoring, wearables
Human Motion	Harnesses human movement	Limited power generation from motion	-	Wearables, healthcare monitoring
Organic	Uses biological reactions	Limited by organic material availability	-	Biomedical implants, environmental monitoring
Hybrid	Combined methods for increased reliability	Complex integration, cost	-	Versatile applications, hybrid energy systems

To ensure autonomy from an energy perspective, the energy harvesting elements in the IoT device's structure must be capable of providing the energy required for its proper operation. Therefore, the prediction of the amount of energy harvested and stored energy is computed using energy harvesting and storage models. Next, we present a brief overview of energy harvesting models presented in the literature. References [127 – 130] applied deterministic models for managing power in energy harvesting devices. In [127], a cooperative Automatic Repeat Request (ARQ) protocol was implemented to align the energy consumption of self-powered devices with their battery recharge rate. This approach showed that cooperative ARQ allows wireless sensors to transmit data efficiently with lower energy usage compared to non-cooperative protocols. [128] and [129] introduced an optimal scheduling scheme, or power management algorithm, for IoT devices to maximize data transmission rates while maintaining energy neutrality throughout the day. Furthermore, [130] focused on an optimal scheduling scheme for an IoT device utilizing two energy sources (solar and wind). The proposed algorithm dynamically adjusts the device's power consumption based on task requirements and utility, leveraging weather forecast data and the storage element's power level at the start of each day.

The deterministic solutions, relying on accurate predictions of system states, are not always practical for the IoT ecosystem. Consequently, attention has shifted towards stochastic models capable of adapting energy management to the uncertainties of energy harvesting. Several approaches [131 – 139] in this direction can be found in the literature. Some utilize the Poisson process (a continuous-time Markov process) [131] or the Markov model [132 – 135]. In recent years, researchers have developed other techniques for energy harvesting modeling, such as the Gama process [136], Gaussian model [137], reinforcement learning methods [138], or the Kalman Filter-based model [139], as discussed below.

The possibility of achieving communication between battery-less IoT devices is highlighted, with emphasis on the significant impact of the devices' turn-on voltage threshold on performance. In reference [136], a stochastic model for an RF harvesting system is proposed, employing the gamma process to model energy stored in the storage element, typically a finite battery. The authors also utilized renewal reward theory, a generalization of the Poisson process, to establish an optimal transmission policy to enhance the operation of the RF harvesting system. In [137], accurate probabilistic energy models for hybrid power harvesting IoT devices are presented. These models allow for sizing the storage unit based on the energy requirements of the device in which it is utilized. The predictability of energy harvesting system parameters, such as harvested, combined, and stored energy, and the efficiency of the recharging process, facilitates the design and performance evaluation of hybrid energy harvesting IoT devices. In [138], a reinforcement learning algorithm is proposed to address access control and continuous power control challenges in an energy harvesting IoT system with limited uplink access channels, comprising multiple user devices and a base station. Simulation results demonstrate that the proposed method outperforms other approaches (e.g., quasi binary power control, discrete power control, modified water-filling) in terms of throughput. Lastly, in reference [139], a platform suitable for Body Sensor Networks (BSNs) is proposed. This platform monitors and records the instantaneous usable power generated by wearable IoT devices with energy harvesting capabilities (solar and TEEH), alongside monitoring human activity and environmental data. To predict usable harvested energy based on environmental parameters (light intensity, temperature difference) and human behavior (activity level), the authors developed and validated a Kalman Filter-based model. The Mean Absolute Percentage Error (MAPE) is utilized for comparison, indicating improved prediction performance of the proposed model compared to other models (e.g., regression, moving average, exponential smoothing) under similar testing conditions.

Table 2 summarizes the aforementioned modeling approaches proposed for different types of energy sources and highlights the goals and the main results obtained.

In Table 2, energy harvesting systems are noted to adopt the Harvest-Store-Use architecture when dealing with unpredictable or non-controllable energy sources. This emphasizes the critical role of energy storage in the design and functionality of energy harvesting IoT devices. As previously mentioned, many energy harvesting approaches operate under the assumption of variable and unpredictable energy generation. This underscores the necessity for efficient management and effective utilization of stored energy in supercapacitors or batteries to ensure continuous and reliable device operation.

Energy harvesting IoT devices typically employ two options for energy storage: rechargeable batteries and supercapacitors, each with distinct advantages and limitations [141]. Some systems utilize both batteries and supercapacitors, offering improved response to high discharge pulses [142]. While batteries are favored for their high energy density, supercapacitors are often chosen due to their extended maximum recharging cycle lifetime, potentially leading to longer device service life. However, supercapacitors, also known as electric double-layer capacitors, fall short of batteries in terms of energy density and suffer from higher self-discharge rates, around 30% compared to 5% in batteries [103, 141]. Modeling the behavior of supercapacitors is crucial for designing energy harvesting IoT devices [143]. Efficient energy modeling allows for the optimal design of energy buffers to maintain uninterrupted operation. Historically, the challenge of designing proper energy buffers was addressed through over-dimensioning [144].

4. CASE STUDY

In this section, we delve into two IoT case study systems where sensing devices are equipped with energy harvesting mechanisms, enabling them to achieve energy autonomy. We provide details on the hardware implementation, as well as considerations and insights gained from the design, implementation, and operational phases. The first case study utilizes solar energy harvesting, while the second relies on RF energy harvesting. Both systems employ environmental BLE (Bluetooth Low Energy) beacons, operating within an IoT scenario (refer to Figure 8), thereby functioning as IoT sensing devices [50, 126]. BLE beacons are a type of wireless sensing system that transmits data to base stations, which can be stationary or mobile [115]. The IoT devices in these case studies, acting as monitoring systems, broadcast the measured parameters, with BLE-enabled terminals (e.g., smartphones) receiving this data. Smartphones running monitoring applications then relay the data to the cloud via Internet connections. Leveraging cloud computing resources, data processing, visualization, and prediction can be performed on the data stored in the cloud.

4.1 SOLAR-POWERED ENVIRONMENTAL BLE BEACON

4.1.1 CASE STUDY SYSTEM OVERVIEW

BLE (Bluetooth Low Energy) is a wireless communication technology [145] that is increasingly utilized in IoT applications due to its simplicity, widespread availability in most contemporary electronic devices, and low power consumption [146, 147]. Various applications, such as retail [124], environmental monitoring [125], indoor localization [148], museum guiding [149], and inventory management [150], have adopted BLE beacons. In the context of the IoT sensor device discussed in [126], it is designed to measure light intensity, temperature, and relative humidity of the environment. We have previously detailed the advantages and limitations of BLE devices in transmitting acquired data to nearby monitoring applications, both in general and specifically for this device, in our previous work [126].

Model Type	Application	Description
Deterministic	[127] - Cooperative ARQ protocols	Balances energy consumption for self-power devices using cooperative ARQ.
Deterministic	[128] and [129] - Optimal scheduling schemes	Maximizes data transmission rate and maintains energy neutrality in IoT devices.
Deterministic	[130] - Optimal scheduling scheme	Optimizes power consumption for an IoT device with two energy-harvesting sources.

Stochastic	[131] - Poisson process	Adapts to uncertainty with Poisson process modeling.
Stochastic	[132]–[135] - Markov models	Utilizes Markov models for stochastic energy management.
Stochastic	[136] - Gamma process	Models energy storage in RF harvesting system with gamma process, optimizing transmission policy.
Stochastic	[137] - Probabilistic energy models	Provides accurate models for hybrid power harvesting IoT devices.
Stochastic	[138] - Reinforcement learning algorithm	Addresses access control and power control with reinforcement learning.
Stochastic	[139] - Kalman Filter-based model	Predicts usable harvested energy using Kalman Filter-based model.

Here, we focus on the energy harvesting mechanism that was used in the device's architecture and the strategies that were implemented for achieving energy autonomy. We achieved energy independence even in the case when a modified variant of the IoT device was fitted with a CCS811 gas sensor [50, 151]. It is a well-known fact that the use of gas sensors in energy-constrained devices, such as wireless sensors, is problematic due to their requirements in terms of power and wake-up times. The work in [50] presents the use of adaptive duty-cycling strategies that resulted in energyefficient autonomous operation of the IoT device.

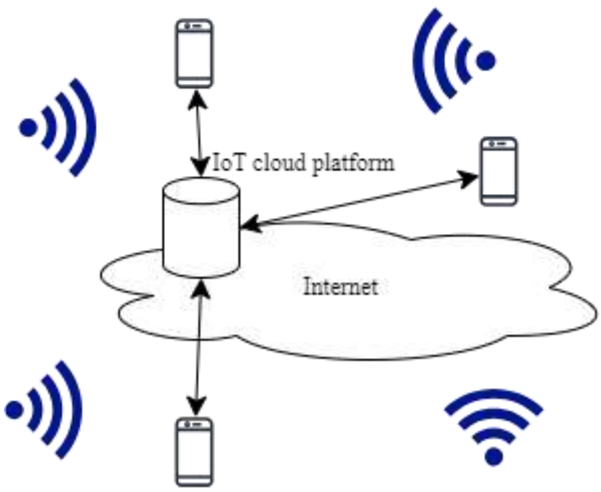


FIGURE 8: IoT scenario for use-case systems' operation

4.1.2 HARDWARE ARCHITECTURE

The IoT device architecture features essential components including a programmable BLE-enabled radio on chip, the Cypress Semiconductor EZ-BLE PRoC Module [152], an SHT21 temperature and relative humidity sensor [153], an MPL115A2 absolute pressure sensor [154], and a PT3001 digital ambient light sensor [155]. For power, it utilizes a bq25504 ultra low-power boost converter with battery management for energy harvesting applications [156], two IXYS KXOB22-04 × 3L amorphous silicon solar cells connected in series [157], a single-cell coin rechargeable battery [158], and two TPS78330DDCT low-dropout linear regulators [159]. Due to the uncontrollable nature of solar energy, the device follows a "generate-store-use" architecture, where energy is harvested from the solar cells, stored in the rechargeable battery, and then utilized to power the device's electronics. Figure 9 illustrates these components, while Figure 10 displays the integrated hardware.

To enhance control over the device's power consumption, two TPS78330DDCT Low-DropOut linear regulators (LDOs) were incorporated. These regulators provide power to both the processing and sensing components of the device, allowing the firmware to manage the power source for both central and sensing functions. With the beacon periodically sampling its sensors, processing acquired data, and broadcasting it, the power supply to the sensors can be toggled off between readings. This approach minimizes the overall power consumption of the system, optimizing its efficiency.

4.1.3 OPTIMIZATIONS FOR ACHIEVING ENERGY AUTONOMY AND RESULTS

The initial findings indicate that the BLE beacon can achieve energy autonomy without the need for advanced power optimization techniques, particularly when the gas sensor is inactive [126]. By setting the processor's clock frequency to 3 MHz, taking sensor readings (temperature, humidity, pressure, light) once per minute, and transmitting an advertisement every 3 seconds, the device drew an average current of 37 µA. This low current draw allows for standalone operation, with the solar cells capable of charging the rechargeable battery within a single day under favorable weather conditions. In this operational scenario, the sensors are powered only during their reading once per minute, with the resulting data used to update the advertisement packet. The control module predominantly remains in sleep mode and wakes up briefly once every three seconds for 3 ms to transmit the advertisement packet, and for 140 ms every minute to communicate with the attached sensors. This optimized power management strategy ensures efficient energy utilization.

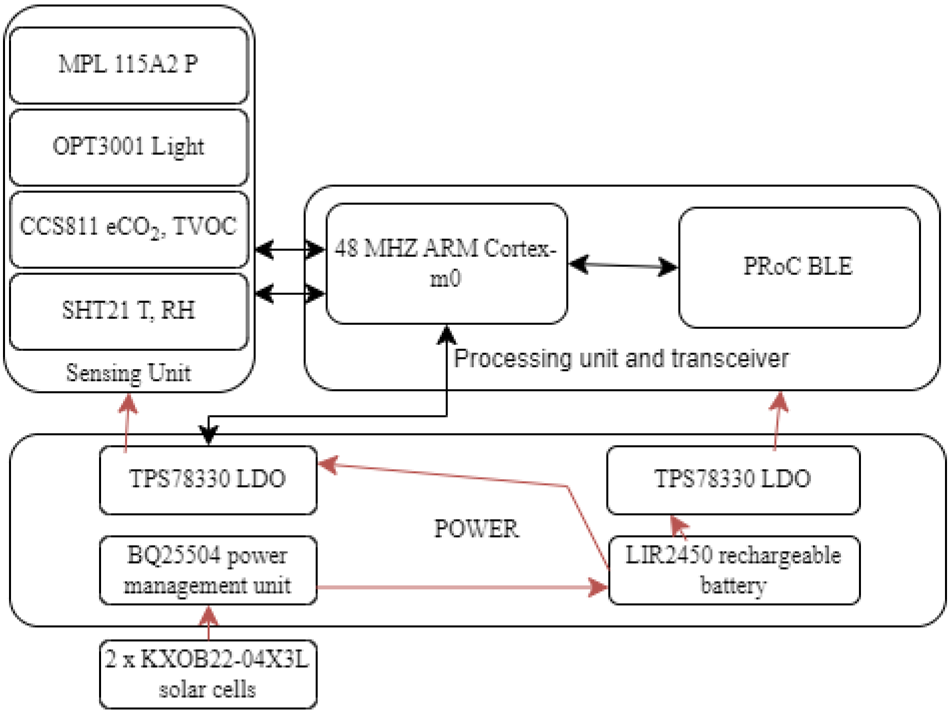


FIGURE 9: Architecture of solar-powered BLE beacon

The incorporation of the CCS811 gas sensor into the IoT device design, providing data on eCO2 and Total Volatile Organic Compounds (TVOC) levels in the air, necessitated more sophisticated energy autonomy mechanisms [50]. These firmware optimizations were required due to the gas sensor's higher power consumption and need for extended wake-up periods. Adaptive duty-cycling strategies were implemented in the firmware of the IoT device, considering factors such as light intensity and the energy stored in the battery. These strategies were crucial for reducing the overall power consumption. Additionally, the advertising interval was increased to 5 seconds from the previous 3 seconds to further lower energy consumption. The IoT device consumes more energy when its sensors are active and taking measurements compared to when transmitting collected data. Therefore, the sensors, including temperature (T), relative humidity (RH), and light intensity, are sampled at different rates based on their power requirements, battery voltage, and light intensity. The T, RH, and light intensity sensors are powered up and read every minute, during which the battery voltage is also measured using a dedicated circuit. If light intensity and battery level exceed certain thresholds, the gas sensor's wake-up period is extended to perform readings. Otherwise, the CCS811 sensor reading is postponed until a future wake-up period with suitable conditions. Through careful selection of threshold values and maximum delay periods for gas sensor readings, efficient activity scheduling enabling energy autonomy is achieved, even under unfavorable weather conditions or day/night cycles, as demonstrated in previous results [50]. This achievement is realized through meticulous dimensioning of energy harvesting circuits, such as the size of solar cells, and efficient hardware and software designs including separate power sources for sensors, battery level measurement circuits, and adaptive duty-cycling strategies.

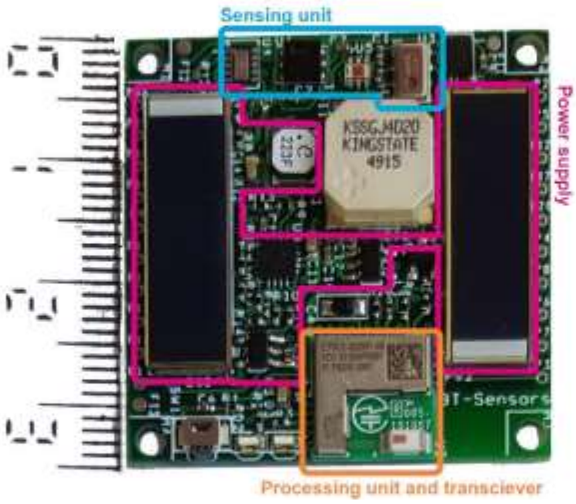


FIGURE 10: Manufactured solar-powered BLE beacon

4.2 RF ENERGY HARVESTING ENVIRONMENTAL BLE BEACON

4.2.1 CASE STUDY SYSTEM OVERVIEW

In the second use case system, we transitioned the power source of the BLE beacon to an RF energy harvesting element, as illustrated in Figure 11. This IoT device also operates on a harvest-store-use architecture, as depicted in the block diagram of the system [4].

The resulting IoT device operates similarly to the previous system described. However, due to the smaller amounts of scavenged energy from RF harvesting elements, powering on the CCS811 gas sensor was not feasible. As a result, the RF energy harvesting BLE beacon can measure temperature, relative humidity, light intensity, and atmospheric pressure.

4.2.2 HARDWARE ARCHITECTURE

In the second use case system, the power supply of the IoT device was replaced by an RF energy harvesting circuit that charges a supercapacitor, as shown in Figure 11. The CCS811 gas sensor, requiring energy levels that the energy harvesting circuit couldn't provide for longer wake-up periods, was removed from the device. The power supply setup includes a P1110 Powerharvester charging module, connected to a 50 mF capacitor for storing the generated energy. This module generates energy from signals in the 850–950 MHz frequency range and charges the onboard supercapacitor that powers the BLE-enabled IoT device. While a capacitor with many charging-discharging cycles is used instead of a rechargeable battery, it suffers from high leakage current (5–10 µA) similar to the sleep current of wireless sensor nodes (∼1–10 µA). In this setup, the 50 mF capacitor discharges from 3.3 V to 2.3 V in less than 5 hours. A GSM phone operating in a band close to the P1110 module's frequency (2G technology), placed 5 cm from the harvester antenna, can charge the capacitor to 3.3 V in under three minutes. Understanding these values and the device's energy profile allows for estimating the required rate at which the energy harvesting mechanism should charge the storage element, enabling adjustments to the system's design. Detailed design and experimental results can be found in [4].

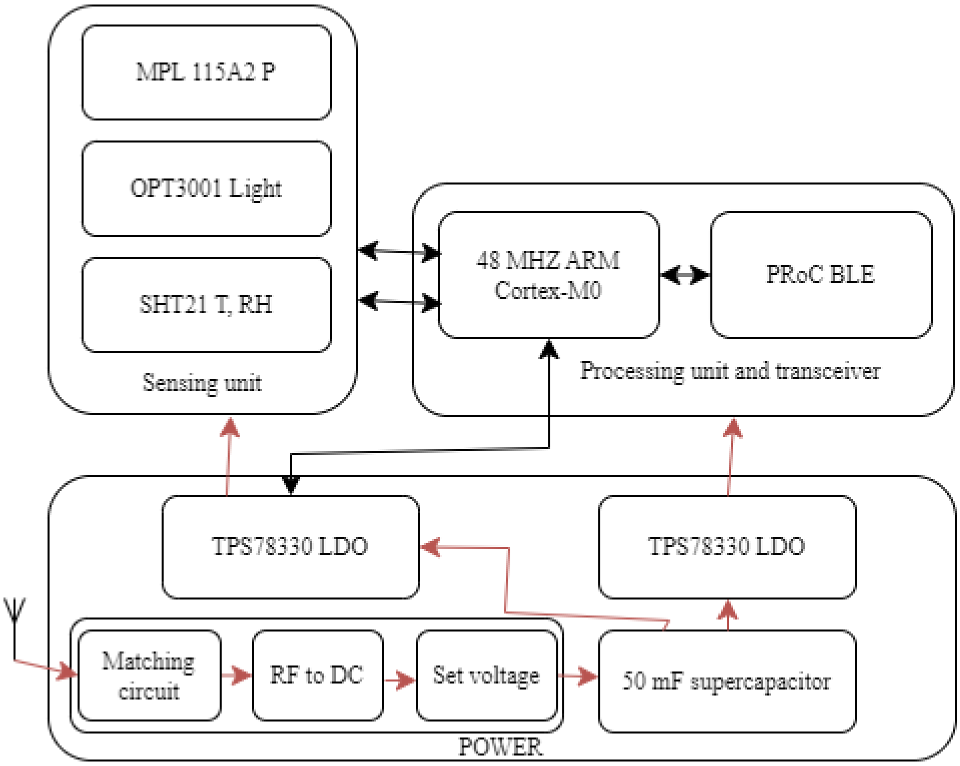


FIGURE 11: Architecture of RF-powered BLE beacon

4.2.3 OPTIMIZATIONS FOR ACHIEVING ENERGY AUTONOMY AND RESULTS

The firmware on the IoT device operates with a simple duty-cycled system where the attached sensors are read every 30 seconds and advertisement occurs every 3 seconds. As our focus was testing the feasibility of RF energy harvesting for such a system, no further optimizations were made on the central unit's application. Our experiments showed that the 30 cm² antenna of the P1110 RF Powerharvester could deliver sufficient power for the IoT device, which samples sensors every 30 seconds and sends advertisements every 3 seconds, when a 2G GSM phone within 10 cm is in an active call. However, achieving this required finding the optimal distance and alignment between the energy source and harvesting component. The high self-discharge current of the supercapacitor poses a challenge, suggesting the need for more efficient energy storage options. Additionally, measuring the signals accurately is crucial due to the rapid current variations of the BLE beacon, demanding measurement equipment with wide input ranges and high sampling rates. Another significant challenge is the miniaturization of hardware for RF energy harvesting IoT devices. While IoT sensors should be small and cost-effective, robust RF energy systems often require larger antennas and more complex circuitry. The study in [4] demonstrated RF energy harvesting's potential for powering IoT devices, but it's essential to note that specific conditions (such as proximity to an active source within the correct frequency range) are necessary for its effectiveness.

4.3 DISCUSSIONS AND LESSONS LEARNT FROM THE CASE STUDY SYSTEMS ENERGY HARVESTING DESIGNS

The development and analysis of the operation of the IoT devices presented here identified several design issues that could be useful for researchers focusing on energy harvesting IoT devices' implementations.

4.3.1 HARDWARE

The hardware design of the two case study systems demonstrated that significant energy savings can be achieved by using simple methods. One such method is the use of a separate power source for the sensors attached to the IoT device. This design allows the software to have direct control over the operation of the sensors, enabling efficient scheduling of their active periods. With this feature, the solar-powered IoT device was able to dynamically adjust the frequency of sensor readings based on the amount of energy generated by the solar cells and the level of charge in the accumulator. This adaptive approach ensures that the sensors are powered only when necessary, reducing overall energy consumption and extending the device's autonomy.

Another useful energy-saving feature is adjusting the operational frequency of the microcontroller. By setting the frequency close to the point where the static component of the current drawn by the IoT device becomes the main consumer, rather than the dynamic component, significant energy savings can be achieved. For example, reducing the operating frequency from 48 MHz to 12 MHz did not noticeably increase the data processing time but led to a considerable decrease in power consumption. This optimization strategy helps ensure that the device operates efficiently while minimizing its energy usage.

4.3.2 ENERGY HARVESTER

I have highlighted an important distinction between energy harvesting methods based on the amount of energy they generate and their physical size. Solar cells and piezoelectric circuits fall into a category that provides sufficient energy for extended periods and allows for miniaturization. On the other hand, RF energy harvesting, while generating smaller amounts of energy at discrete moments, tends to occupy more space. This poses a challenge for energy harvesting IoT devices, which need to be small and have simple designs. Currently, the first category (solar cells and piezoelectric circuits) seems to more easily meet these requirements. However, for RF energy harvesting, one potential application could be embedding the antenna into objects such as clothing, especially for wearable IoT devices. This way, the antenna can utilize ambient RF signals to power the device without adding bulk.

Absolutely, an energy budget of 50 to 60 µAh generated by an energy harvesting circuit could indeed ensure autonomous operation for a variety of IoT devices without relying on batteries as the main power supply. Considering the expected proliferation of billions of IoT devices in the coming years, energy harvesting presents a compelling opportunity for significant energy savings. This approach not only reduces the need for batteries but also conserves materials and effort required for their manufacturing and disposal, contributing to more sustainable IoT ecosystems.

4.3.3 SOFTWARE

Algorithms for optimizing energy consumption are crucial for overcoming challenges such as the unpredictability of energy sources. In the case of the first use case system, which relies on solar energy, the firmware plays a key role in adapting the IoT device's operation to reduce energy usage during unfavorable conditions like cloudy weather or nighttime when energy storage is low. Software algorithms are essential for predicting harvested energy from solar sources.

On the other hand, in RF energy harvesting, hardware optimizations become more critical for efficient operation of the IoT device. Algorithms that selectively send data based on its variation, such as sending slow-changing data less frequently, can significantly increase energy efficiency in both solar and RF energy harvesting scenarios. This highlights the importance of a combination of hardware and software optimizations to achieve optimal energy harvesting and consumption for IoT devices.

4.3.4 COST

Our case study systems show that energy harvesting leads to an increase of the cost of an IoT device of 15 to 20 Euros. However, in many designs, energy harvesting could provide at least the energy required for sleep mode periods and for leakage currents. If we assume a sleep current between 3 and 10 µA, this could lead to savings of 26.3 to 87.6 mAh for the main energy source, that could be a battery. For an energy efficient IoT device, this could mean doubling of its lifetime, from 5 to 10 years.

5. TECHNICAL CHALLENGES

Even if have witnessed recent advances in the design and development of energy harvesting devices over the past decade, several technological challenges still need to be addressed before the manufacturing of self-sustainable IoT devices becomes prevalent. Some of them are:

Harvested energy modelling: A balance between the generated power and the consumed power must be maintained. This implies the efficient power profiling of IoT devices and the adaptation of their operation to the amount of harvested energy. The availability of the harvested energy varies mostly with time in a non-deterministic manner. Therefore, the estimation of the amount of energy scavenged is computed using prediction techniques and conventional power management approaches (i.e., Maximum Power Point Tracking (MPPT) and software Phase Locked Loops (PLL)) are applied to manage the power coming from the energy sources. Recently proposed energy forecasting models should be improved to provide accurate results, while the power management choices should be made to minimize the loss of energy. Additionally, the power source must provide enough energy for the following tasks: data processing operations, transmission and/or receive actions, and sleep periods. In most cases, it is not the data processing that is the most energy-demanding task. It is the transmission and reception of data over the wireless Internet. Therefore, future researchers should develop optimized consumption models to minimize the energy cost during wireless data transmissions and investigate novel techniques to adapt the wireless communication protocols according to the energy harvesting process' characteristics.

Harvested energy storage: This involves the development of suitable storage elements such as rechargeable batteries and supercapacitors because the technology used for storing the harvested energy affects the cost, size, and the operating life of the IoT devices. Batteries have high energy densities, but they are not well suited for long-life IoT devices due to the cycling degradation phenomenon [161]. Moreover, both high and low temperatures reduce their capabilities. Supercapacitors have lower energy density than batteries, but cyclic degradation does not affect them. Furthermore, supercapacitors suffer from increased current leakage that would consume a large part of the harvested energy. Therefore, future researchers should investigate new techniques that can find the best candidate for harvested energy storage which must meet the following criteria: low cycling degradation, low current leakage, high energy density, and continued operation even in harsh environments such as at very low and very high temperatures.

Energy harvesting from multiple sources: There are cases wherein a single source of energy harvesting is insufficient to power IoT devices. By combining energy from multiple sources, the reliability of IoT devices can be increased. The work in [162] presents the recent developed architectures and techniques of low power management circuits that use energy harvested from multiple heterogeneous sources of energy. The analysis highlights that the proposed architectures are suitable for specific applications. For example, the complementary use of harvesters or the Power ORing topology are simple schemes appropriate in cases where it is not expected that all the input energy sources deliver a significant amount of power at the same time. The multiple input switched-inductor and switched-capacitor converter architectures are also used to combine energy for heterogeneous sources. Regardless of the chosen architecture, designers must consider the development of configurable impedance matching schemes for the purpose of MPPT control. Researchers should also focus their attention on the development of intelligent algorithms capable of selecting the input sources of energy depending on their availability thereby eliminating the need for the energy storage element.

Size and cost efficiency: There are situations where the size and the weight of IoT devices are critical (i.e., wearable and implantable IoT devices). But these devices produce a small amount of energy which is not enough to be used to perform their main functions (i.e., powering the device and the attached sensors, data transmission). Small-scale harvesting solutions (micro, nano) that can power IoT devices and support the operation of other functions (i.e., monitoring the health status of patients, acting as stimulators for regenerating tissues) must be developed considering the low cost of fabrication. The scientific literature emphasizes that PEHs can be effectively used for powering small and very-small IoT devices. Therefore, future researchers should develop new eco-friendly materials to enable micro and nanofabrication of PEHs with improved flexibility and output power density. Recent advances in the field of microelectronics are promising and can be used to develop robust, miniaturized, low power, and low-cost energy harvesters.

Environmental impact with renewable energy sources: Renewable energy sources help to mitigate environmental pollution, and thus, they are used to develop new IoT devices because this industry has experienced a significant growth in the past few years. Batteries used in IoT devices without energy harvesting mechanisms eventually get depleted and, in some cases, they are thrown away in several weeks or months. If there are no battery recycling mechanisms, then the environment suffers. The challenge in this case is the development of energy harvesting IoT devices with a lifetime significantly longer than the one provided by batteries. Also, it is worth noting that some energy harvesting IoT devices employ toxic or rare materials (i.e., bismuth telluride for TEEHs, lead zirconate titanate for PEHs, cadmium for PV). Therefore, the use of eco-friendly materials, such as electroactive polymers, carbon nanowire semiconductors, to design the electronics components of the energy harvesting IoT devices is another challenge that must be addressed. Biodegradable and biocompatible IoT devices must be considered by developers of such devices for a sustainable future.

6. CONCLUSION

Energy harvesting technologies have garnered significant interest from research communities and industries alike, especially in the realm of designing self-powered IoT devices. This article provides an analysis of the energy harvesting techniques primarily employed in the IoT environment. It is evident that various energy harvesting methods offer unique advantages and challenges.

Some energy harvesting technologies, such as small size photovoltaic (PV) cells and piezoelectric devices, can provide substantial energy for extended periods. These technologies are efficient at converting ambient light or mechanical vibrations into usable electrical energy. On the other hand, there are methods like RF energy harvesting that yield small amounts of energy at discrete moments, requiring larger circuits for energy capture. However, RF energy harvesting does not rely on specific cycles like day/night or weekdays/weekends, making it versatile but requiring careful design considerations.

The choice of energy harvesting technique depends on several factors, including the parameter to be measured, the IoT device's use case scenario (fixed/mobile, surface/built-in), and its location (indoor/outdoor). For instance, solar energy harvesting is effective for outdoor devices with access to sunlight, while RF energy harvesting could be suitable for mobile IoT devices that need to operate in various environments without a predictable power source.

To illustrate the potential of solar and RF energy sources, two IoT case study systems from previous work are described. These systems incorporate energy harvesting mechanisms and provide valuable insights into their design, hardware implementation, and operational considerations. The first case study system utilizes solar energy harvesting, demonstrating how a generate-store-use architecture can effectively power an IoT device with a rechargeable battery. Through firmware optimizations and adaptive duty-cycling strategies, the device efficiently manages its power consumption, adapting to varying energy availability.

In the second case study system, RF energy harvesting is employed, replacing the power source with an RF energy harvesting circuit charging a supercapacitor. This system faces challenges such as energy limitations for certain sensors and the need for optimal alignment between the energy source and harvester. Despite these challenges, the system demonstrates the feasibility of using RF energy harvesting for IoT devices.

Looking ahead, several technical challenges need addressing to facilitate the widespread deployment of energy harvesting solutions for IoT. These challenges include:

Improving energy forecasting models to provide more accurate predictions of harvested energy.

Developing optimized consumption models to minimize energy costs during wireless data transmissions.

Investigating novel techniques to adapt wireless communication protocols based on energy harvesting characteristics.

Overcoming hardware challenges such as miniaturization and efficient signal measurement for RF energy harvesting.

In conclusion, energy harvesting technologies offer promising solutions for self-powered IoT devices, with each method having its advantages and challenges. By carefully considering the application, environment, and specific requirements, the appropriate energy harvesting technique can be chosen to enable long-term autonomy and sustainability for IoT deployments. The case study systems discussed provide valuable insights into the practical implementation of energy harvesting in IoT devices, paving the way for future advancements in this field.

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