3-4-2021

Energy Harvesting Techniques for Internet of Things (IoT)

Teodora Sanislav
Technical University of Cluj-Napoca, Romania

George Dan Mois
Technical University of Cluj-Napoca, Romania

Sherali Zeadally
University of Kentucky, szeadally@uky.edu

Silviu Corneliu Folea
Technical University of Cluj-Napoca, Romania

Received February 17, 2021, accepted February 25, 2021, date of publication March 4, 2021, date of current version March 16, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3064066

Energy Harvesting Techniques for Internet of Things (IoT)

TEODORA SANISLAV[1], (Member, IEEE), GEORGE DAN MOIS[1], (Member, IEEE), SHERALI ZEADALLY[2], (Senior Member, IEEE), AND SILVIU CORNELIU FOLEA[1], (Senior Member, IEEE)

[1]Automation Department, Technical University of Cluj-Napoca, 400114 Cluj-Napoca, Romania
[2]College of Communication and Information, University of Kentucky, Lexington, KY 40506, USA

Corresponding author: Teodora Sanislav (teodora.sanislav@aut.utcluj.ro)

ABSTRACT The rapid growth of the Internet of Things (IoT) has accelerated strong interests in the development of low-power wireless sensors. Today, wireless sensors are integrated within IoT systems to gather information in a reliable and practical manner to monitor processes and control activities in areas such as transportation, energy, civil infrastructure, smart buildings, environment monitoring, healthcare, defense, manufacturing, and production. The long-term and self-sustainable operation of these IoT devices must be considered early on when they are designed and implemented. Traditionally, wireless sensors have often been powered by batteries, which, despite allowing low overall system costs, can negatively impact the lifespan and the performance of the entire network they are used in. Energy Harvesting (EH) technology is a promising environment-friendly solution that extends the lifetime of these sensors, and, in some cases completely replaces the use of battery power. In addition, energy harvesting offers economic and practical advantages through the optimal use of energy, and the provisioning of lower network maintenance costs. We review recent advances in energy harvesting techniques for IoT. We demonstrate two energy harvesting techniques using case studies. Finally, we discuss some future research challenges that must be addressed to enable the large-scale deployment of energy harvesting solutions for IoT environments.

INDEX TERMS Energy efficiency, energy harvesting, Internet of Things, IoT device, wireless sensor networks.

I. INTRODUCTION

Fifteen years ago, the International Telecommunications Union (ITU) published its first report on the Internet of Things (IoT) [1]. The IoT paradigm was first defined as a new dimension added to the world of Information and Communication Technologies (ICTs) that allows making connections for anyone and anything, anytime and anywhere to create a new dynamic network of networks [1]. Today, IoT is no longer an emerging trend. It has become one of the most important technologies of the current century with applicability in many industries such as transportation, energy, civil infrastructure, smart buildings, environment monitoring, healthcare, defense, manufacturing, and production. IoT continues to grow. Experts predict that, by 2025, about 22 billion IoT devices will be connected to the Internet and will communicate in this IoT environment [2].

The associate editor coordinating the review of this manuscript and approving it for publication was Guangjie Han.

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

- IoT devices (sensors and actuators) are responsible for collecting data or controlling a certain process.
- IoT connectivity (protocols, gateways) is responsible for transferring data in the online, cyber-physical world.
- The IoT cloud stores data and it is also the place where decisions are made.
- IoT analytics and data management are responsible for processing the data.
- End-user devices and user interfaces help to control and configure the system.

Each of these components must address significant scientific and technological challenges for achieving efficient and scalable implementations. For example, *the energy efficiency paradigm associated with IoT devices must be considered early on during their design phase* [4]. Enabling a seamless flow of information throughout the IoT ecosystem is another important challenge because wireless connectivity is highly complex, and the fast-evolving wireless standards contribute to this. The development of new Artificial Intelligence (AI) techniques to analyze huge amounts of data and make real-time decisions is another major challenge. Also, security and privacy must be considered because existing security protocols such as Data Encryption Standard (DES), Advanced Encryption Standard (AES) and Rivest, Shamir, and Adelman (RSA), are not suitable for IoT devices due to their resource (memory, processing power) constraints and heterogeneity [5]–[7].

We describe the challenge associated with the energy efficiency paradigm for some IoT devices (such as wireless sensors) below. The IoT vision benefits from the features of Wireless Sensor Networks (WSNs) [8], [9] and relies on these systems for gathering data about the environment and for performing actions following the analysis of the collected data. IoT uses Internet Protocol (IP) connectivity for assuring that every one of its components, or "things", has a distinct address, while WSNs do not necessarily require a connection to the Internet. However, due to the continuously increasing power of microelectronics combined with their decreasing costs, improved power efficiency of hardware technologies along with better wireless communication protocols, WSNs have become a vital component of the IoT ecosystem. WSNs can 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.

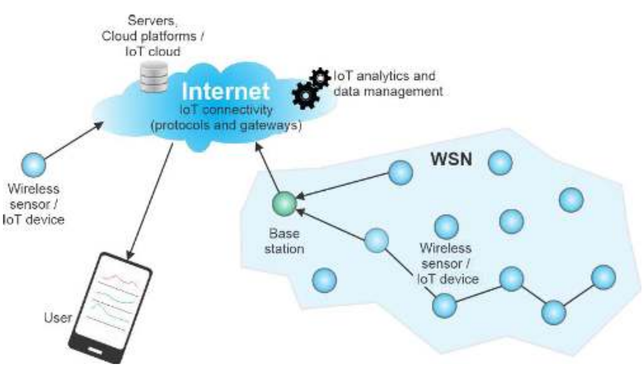


FIGURE 1. **Typical IoT scenario including Wireless Sensor Networks (WSNs).**

The use of wireless sensor networks has proven to be beneficial in specific applications where access is difficult, such as remote locations or on moving parts of machinery [19]–[22]. Generally, a wireless sensor is made up of four main components, namely the sensorial part, the processor, the transceiver, and a power supply, as Figure 2 shows [23]. In general, wireless sensors have limited capabilities in terms of processing power and storage and must operate on small

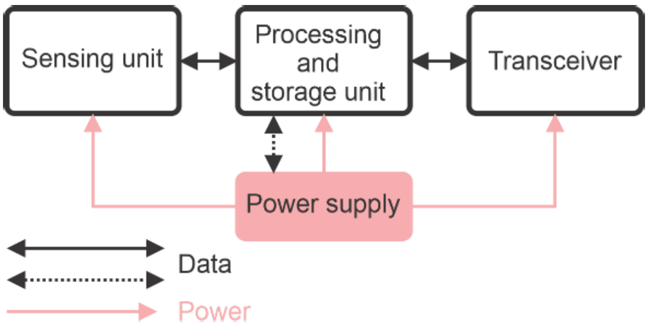


FIGURE 2. **Wireless sensor (IoT device) components.**

amounts of energy because the power source, in most of the cases is a battery which has limited capacity. Other challenges encountered in the deployment of solutions that rely on wireless sensors include reliable communication, coverage and deployment issues, security, QoS (Quality of service) assurance, and the efficient management of large amounts of data [10]. Therefore, the long-term and self-sustainable operation of wireless sensors (IoT devices) is a critical issue and must be addressed properly. Energy Harvesting (EH) technology is an environment-friendly solution that has the potential to extend the lifetime of these sensors. Energy harvesting refers to the harnessing of energy from various external sources and its conversion into electricity.

This work deals with the analysis of energy harvesting techniques suitable for IoT devices. We summarize our research contributions as follows:

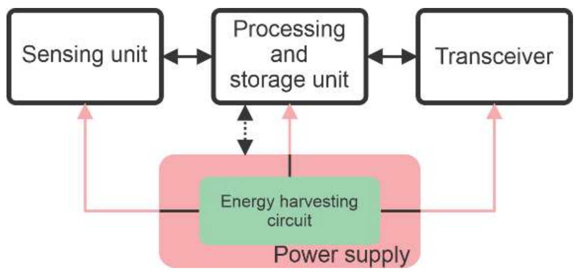
- We motivate why energy harvesting is important for the IoT ecosystem.
- Based on a comprehensive review of energy harvesting solutions for IoT, we analyze different techniques to harvest energy from various sources.
- We present two IoT energy harvesting devices developed by the authors, along with considerations regarding their design, implementation, and testing.

We organize the rest of the article as follows. The second section highlights why energy harvesting is important for IoT. In this section, we highlight the limitations of using batteries as the main power source for wireless sensors. The third section presents an overview on energy harvesting techniques that can be used in IoT. We present a classification of these techniques according to the sources from which energy is harvested energy. We analyze recently proposed energy harvesting techniques for IoT. In the fourth section we describe the energy harvesting models and consumption models that have been proposed for implementing energy harvesting IoT devices. We then present two case studies from our previous works on solar energy harvesting and Radio Frequency (RF) energy harvesting. We describe the architecture, operation, and energy characteristics of a solar powered environmental IoT device based on Bluetooth Low Energy (BLE) communication. We present a prototype for a BLE-enabled environmental beacon, powered by a RF energy harvesting element in the fifth section. The sixth section discusses a few technical challenges that still need to be addressed on the design and development of energy harvesting devices even though progress has been made in recent years on self-powered IoT devices. Finally, we make some concluding remarks in the final section.

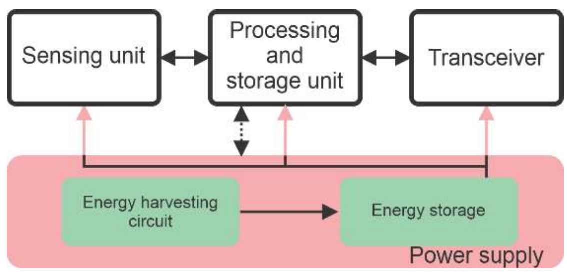
II. MOTIVATION FOR ENERGY HARVESTING IN IOT

It is desirable for the network lifetime to be as long as possible. Therefore, energy efficiency and long battery lifetime are of crucial importance in the design and development of wireless sensors (IoT devices). However, a battery has a finite capacity and, even though there have been breakthrough developments in communication protocols, operating systems, and in the implementation of powerful power management mechanisms, highly efficient MAC (medium access control) and routing protocols, it will eventually get depleted. To ensure the operation of the network, costly maintenance operations for battery replacement must be performed. The scale of wireless sensor networks coupled with sensor placement, often in inaccessible locations, make these maintenance operations difficult in many cases [24]. The use of batteries as power supply for wireless devices has other drawbacks besides their ability to provide power for a finite amount of time. These include reduced energy densities and leakage, that discharges the battery even when it is not used. Moreover, the application space of batteries is limited by the impact of temperature on their proper operation, extreme conditions leading to capacity and power losses [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]. Currently, there is also a generalized trend of reducing the environmental impact of information and communication technology, and this also applies to wireless sensors, where the goal is toward the achievement of sustainable and energy efficient systems [29]. These are some of the reasons why energy harvesting elements are included in the design of current wireless sensors. These energy harvesting components can act as secondary power sources or can completely replace batteries. The use of energy harvesting extends mote's lifetime by replenishing its energy from an energy source, such as solar cells, vibration or fuel cells, acoustic noise, or mobile suppliers (robots) [10]. In this way, the long-term and self-sustainable operation of wireless sensors, one of the most important issues in the widespread use of IoT, is assured [29].

Energy harvesting or *energy scavenging* is the process through which energy from external sources, such as mechanical load, vibrations, temperature gradients, or light, is captured and converted to obtain relatively small levels of power supplied to electronic devices [4], [30]. The intake of energy from the surrounding environment leads to a green energy source that replaces primary batteries or charges secondary cells and represents a cost-effective and environmentally sound method for 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 Harvest-Store-Use [32]. Figure 3 shows the two distinct architectures for a wireless sensor node with energy harvesting elements. Depending on the configuration of the system, belonging to one of the two architectures, its power generation part includes specific energy harvesting circuits that convert ambient energy to Direct Current (DC) energy, power management units that increase the efficiency of power generation and its use, and storage elements, that can store energy and power the electronics. All these components and their associated characteristics and actions are the subject of intense research efforts, that target the manufacturing of energy-autonomous wireless sensors when deployed in the IoT environment.



(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. (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].

III. ENERGY HARVESTING TECHNIQUES FOR IOT

For energy harvesting several energy sources can be considered. These can be classified into the following categories according to the sources from which the harvested energy

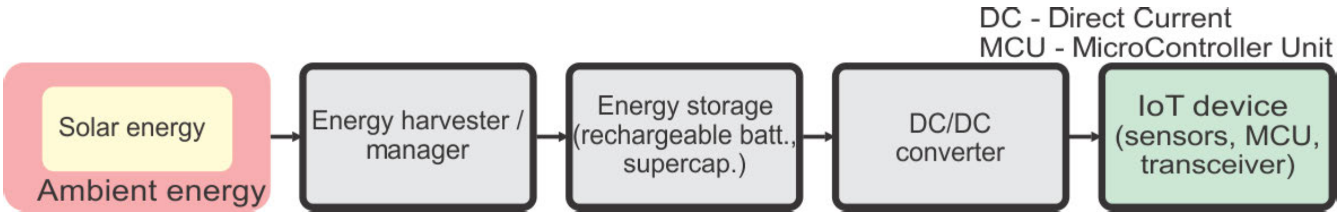


FIGURE 4. Main components of a solar energy harvesting system. Adapted from [47].

comes: ambient, mechanical, human, organic and hybrid. The ambient energy sources are available in the environment and can be easily accessed without any costs. These ambient sources can in turn be divided into the following categories: solar, Radio Frequency (RF), thermal, wind, and hydro based energy sources [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.

A. AMBIENT ENERGY HARVESTING

Solar and RF are the main ambient energy sources that are naturally or artificially always present in the environment and can be considered in making self-powered devices for the IoT ecosystem. This is why in this work we focus only on these ambient sources.

1) SOLAR ENERGY HARVESTING

Solar power is the most abundant energy source on earth, with approximately 173 × 1012 kW of energy produced continuously, a quantity that exceeds by far the world's demand and use [33]. The total energy that reaches the earth's surface annually is approximately 3.4 × 1024 J, an amount that is 7000 to 8000 times higher than the yearly primary energy consumption of the globe [34]. This energy is harvested through helio-chemical (photosynthesis), helio-electrical (photovoltaic converters), and helio-thermal (thermal energy production, solar water heaters) processes [35]. The helio-electrical process is based on the Photo-Voltaic (PV) effect, that can be observed when two dissimilar materials convert solar rays into DC (direct current) power when struck by light [24]. The device that is used for generating electricity from sunlight is the solar cell or the photovoltaic cell, that is a solid-state electrical junction device [24]. It is usually built from silicon, using a process like the one used in the manufacturing of 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]. The parameter used for comparing their performance is their efficiency which is defined as the ratio of the maximum output power to the incident light power under 100 mW/cm2 illumination [37]. The first category (mono-crystalline PV cells) has the highest efficiency, between 15 and 24%, but the corresponding mono-crystalline PV cells are the most expensive. The second group, made up of polycrystalline PV cells, has an efficiency between 14 and 20%, while thin-film cells are the cheapest, but with an efficiency lower than 13.2% [36].

In the context of wireless sensors, the use of solar cells for harvesting energy from the environment is a mature technique and is the most common mechanism used for prolonging the lifetime of the power supply [38]–[40]. Solar cells offer the highest power density, of approximately 15 mW/cm2, as compared to various other energy harvesting techniques [41]. Even though solar power is uncontrollable, and the conversion efficiency is affected by the day-night cycle, seasonal changes, weather conditions, and ambient temperature, it can be predicted and modeled so that adequate strategies are adopted for assuring continuous power to electronic devices [42]–[46]. To ensure uninterrupted operation (during the periods such as night and the presence of clouds when ambient light is not available) of the device powered by solar energy harvesting components, an architecture that includes storage elements, as Figure 4 shows, is the most common [47], [48]. The energy storage can be a rechargeable battery, a supercapacitor, or a combination of the two with each choice having its own advantages and limitations. The power is stored when the amount generated exceeds the consumption of the device, or when it is in sleep or inactive mode and this stored power is used when the energy source is missing or when required by the system [48]. PV cells are a well-known technology which have been used in a wide range of IoT devices. When PV technology is used in conjunction with adequate energy storage, power consumption optimization, appropriate circuit design and dimensioning, we can develop efficient energy autonomous devices [49]–[53].

Energy harvesting using PV technology was initially intended for outdoor use. PV cells have been designed mainly for generating energy from sunlight with conversion efficiencies in indoor environments having smaller values as compared to higher conversion efficiencies with outdoor environments [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]. Furthermore, significant progress has

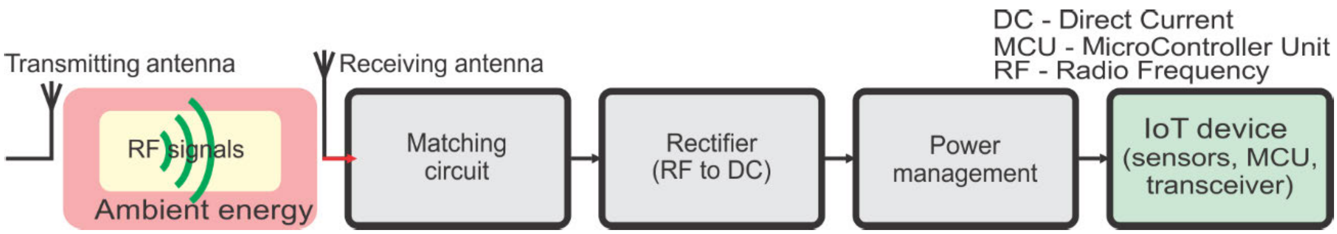


FIGURE 5. Main components of a RF energy harvesting system. Adapted from [61].

also been made in the development of energy supplies for moderate power systems, that consume power in the range of 1 to 10 W, combined with the current popular use of low-power IoT devices requiring between 10 and 100 mW [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) RF ENERGY HARVESTING

Wireless Internet, radio and satellite stations, and digital multimedia broadcasts are sources of RF or electromagnetic signals, between 3 kHz and 300 GHz of frequency spectrum, that can be converted into electrical energy with the help of an antenna and a rectifier circuit, as Figure 5 shows. This type of energy exists around us (indoors and outdoors) at different levels, and it is always available (day or night). This energy can be retrieved without limit, but it has several disadvantages such as low density and low efficiency that is inversely proportional to 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].

B. 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.

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) 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.

C. 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].

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 duty-cycled, 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.

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 / cm^3 and 919.01 μW / cm^3, 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 $\sim$0.1 μW / cm^2 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.

D. BIOENERGY HARVESTING

There are also more special types of energy harvesting. For example, the use of plants for generating the energy required for powering wireless sensors has been investigated in [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.

E. HYBRID ENERGY HARVESTING

There are cases wherein the scavenging of energy from a single source does not generate the amount of power required for the operation of the IoT device at all times. This challenge led to the design of systems that include multiple energy harvesting units, combined with energy storage components [99]. An example is solar energy harvesting. As we have mentioned earlier, generating DC from light can assure the required energy for the operation of wireless sensor nodes. However, the main drawback of using solar energy is its reliability, that is affected by weather conditions and spatial-temporal factors, such as the Sun's position during 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.

IV. ENERGY HARVESTING MODELING

The previous section presented the main energy sources and energy harvesting technologies that can be used to develop IoT devices. Regardless of the technology used, from the design phase of IoT devices with energy harvesting characteristics, we must maintain a balance between the generated and stored power and that which is consumed.

In this context, various energy harvesting models and consumption models have been proposed for two main approaches, namely, Harvest-Store-Use and Harvest-Use (not very common and not suitable for energy sources that are uncontrollable or unpredictable). The energy harvesting models used in the Harvest-Store-Use approach take into account the capacity of the storage element (the harvested energy can always be stored, or the harvested energy can be stored up to a limit and the rest is lost). Also, the harvested energy can be modeled as a deterministic or a stochastic process. If the incoming energy and its fluctuations are known in advance, as in the case of predictable energy sources, the deterministic model is suitable. Otherwise, the stochastic approach is the right one. However, in each one of the cases, the basic idea for assuring battery-free operation for IoT devices is to harvest at least the amount of energy required for the proper operation of the electronics. Usually, the power source must provide enough energy for data processing operations, transmission

TABLE 1. Analysis of Energy Harvesting Techniques.

Energy source	Technology	Power density	Advantages	Disadvantages	Application domains
Solar	PV cell	10 - 100 mW / cm^2 (outdoor) < 100 µW / cm^2 (indoor)	High-output voltage Low fabrication costs Predictable	Unavailable at night Non-controllable	Environment monitoring, healthcare, agriculture
RF	Antenna	0.01 - 0.1 µW / cm^2 1- 10 mW / cm^2	Available anywhere, anytime Predictable Controllable	Distance dependent Low-power density	Environment monitoring
Mechanical vibrations and pressure	Piezoelectric	4 - 250 µW / cm^3	High-power density No external voltage source Simplicity design and fabrication Controllable	Highly variable output Unpredictable	Infrastructure monitoring, automotive
	Electromagnetic	300 - 800 µW / cm^3	High-output currents Robustness Low-cost design Controllable	Relatively large size Unpredictable	
	Electrostatic	50 – 100 µW / cm^3	High-output voltage Relatively larger output power density Possibility to build low-cost devices Controllable	Requires bias voltage Unpredictable	
Human heat	Piezoelectric Pyroelectric	< 35 µW / cm^2	Sustainable and reliable Available Controllable	Low-power density Unpredictable	Healthcare
Biomechanical	Electromagnetic Piezoelectric Triboelectric Electrostatic	< 4 µW / cm^3 < 300 µW / cm^3	Available Controllable	Low-power density Unpredictable	Healthcare
Bio [102]	Metal electrodes	Extremely low wattage	Available Controllable	Extremely low wattage Suitable for nanoscale electrical devices	Environmental sensing in agricultural applications

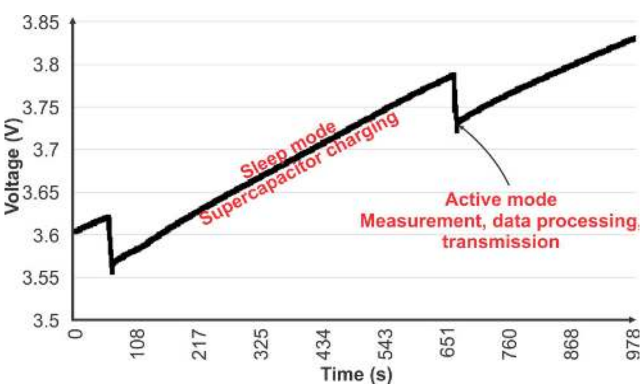


FIGURE 6. Voltage on the storage element (supercapacitor) during operation - T and RH Wi-Fi sensor [53].

and/or receive actions, and sleep periods. Figure 6 shows the voltage on a supercapacitor that is charged by a solar cell which powers a temperature sensor and a relative humidity wireless sensor. These sensors send data periodically to a cloud platform through the Internet. The graph indicates a favorable situation wherein the solar cell is capable to charge the storage element with enough energy for assuring autonomous operation.

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 low-power operation must be scheduled and further modified

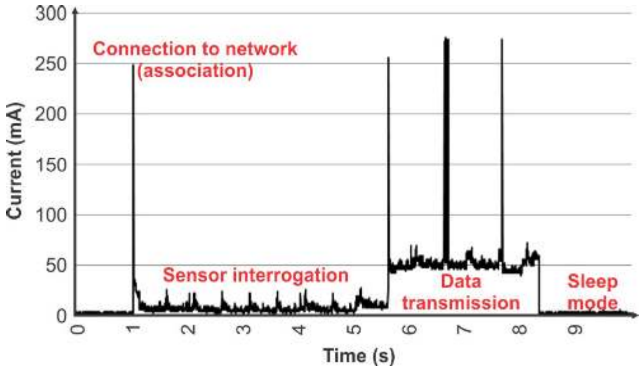


FIGURE 7. Profile of the current drawn by a Wi-Fi sensor during wakeup (T, RH, P, CO2, and light intensity) [126].

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].

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.

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.

In [127]–[130], the authors applied deterministic models for power management of the energy harvesting devices. The approach in [127] uses cooperative Automatic Repeat Request (ARQ) protocols to balance the energy consumption of self-power devices to match their own battery recharge rate. The research has shown that cooperative ARQ enables wireless sensors to efficiently transmit data using lower levels of energy than in non-cooperative protocols. In [128] and [129], the authors describe an optimal scheduling scheme (power management algorithm) for IoT devices to maximize the average data transmission rate and to maintain the energy neutrality of these devices over a day. The work in [130] highlights an optimal scheduling scheme for an IoT device that uses two energy-harvesting sources (solar and wind). The proposed algorithm optimally sets the overall IoT device power consumption based on the utility and on the energy required by tasks, and uses the weather forecast information available at the beginning of each day and the power level of the storage element.

Since the solutions developed based on the deterministic approach need accurate predictions of the system state, which are not always applicable to the IoT ecosystem, attention has shifted to stochastic models capable to adapt the energy management to the uncertainty of the energy harvesting method. Many approaches [131]–[139] in this direction are found in the literature. Some of these approaches use the Poisson process (which is a continuous-time Markov process) [131] or the Markov model [132]–[135], but in recent years researchers have developed other techniques that would be suitable in the energy harvesting modeling process, such as the Gama process [136], the Gaussian model [137], reinforcement learning methods [138], or the Kalman Filter based model [139] as we discuss below.

The work in [135] introduces a stochastic model that uses Markov Chain theory to estimate the performance of battery-less IoT devices (using a capacitor as storage element) for uplink and downlink transmissions. The proposed model takes as inputs the current consumption of different device states, the capacitance, the energy harvesting power, how often a transmission will take place, the probability of receiving a downlink packet, the uplink and downlink packet size, and the Spreading Factor to be used. The Spreading Factor is the amount of spreading code applied to the original data signal and has values between 7 and 12 [140]. The model determines the uplink Packet Delivery Ratio achievable and the probabilities of successfully receiving downlink packets. The authors evaluated the performance of the proposed model in terms of the device configuration, application behavior, and environmental conditions. The results show that a capacitor of 47 mF can support a Spreading Factor of 7 for uplink and downlink at an energy harvesting rate of 1 mW, even when more than once per minute data transmissions are performed. A Spreading Factor of 11 can be supported by a supercapacitor of 1 F at an energy harvesting rate of 10 mW.

Also, the authors stated that it is possible to achieve communication between battery-less IoT devices, but it must be pointed out that the turn-on voltage threshold of these devices significantly affects their performance. In [136], the authors proposed a stochastic model for a RF harvesting system that uses the gamma process to model the energy stored into the storage element (in this case a finite battery). They also used the 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], the authors presented single form accurate probabilistic energy models for hybrid power harvesting IoT devices. These models enable the dimensioning of the storage unit depending on the energy requirements of the device in whose structure it is used. Furthermore, the design and performance evaluation of hybrid energy harvesting IoT devices is facilitated by the predictability of energy harvesting systems parameters, such as the amounts of harvested, combined, and stored energy, and the efficiency of the recharging process, that is achieved in the proposed methodology. The authors of [138] proposed a reinforcement learning algorithm for solving the access control and continuous power control problems in an energy harvesting IoT system having limited uplink access channels. The energy harvesting IoT system analyzed is composed of multiple user devices and one base station. Simulation results have shown that the method proposed achieves better performance than other existing approaches (i.e., quasi binary power control, discrete power control, modified water-filling) in terms of throughput. The authors of [139] propose a platform suitable for BSNs. The BSN monitors and records the instantaneous usable power generated by wearable IoT devices with energy harvesting characteristics (solar and TEEH), while monitoring human activity and environmental data. To predict the amount of 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 used to compare the prediction performance. The value of this metric for the proposed model is better compared with other models (regression, moving average, and exponential smoothing) used in the same 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.

As Table 2 shows, energy harvesting systems adopt the Harvest-Store-Use architecture in the case of unpredictable or non-controllable energy sources. Therefore, energy storage is of paramount importance in the design and operation of energy harvesting IoT devices. As pointed above, many energy harvesting designs assume that energy generation is not constant, and can only be predicted, and therefore the efficient management and proper use of the energy stored in supercapacitors or batteries is required.

The two options for energy storage in energy harvesting IoT devices include rechargeable batteries and supercapacitors, each one of them having their own advantages and limitations [141]. There are also systems that include both batteries and supercapacitors, leading to energy supplies that respond better to high discharge pulses [142]. Batteries are the main choice because of their high energy density, but supercapacitors are more often considered due to their high maximum recharging cycle lifetime, that can result in longer service life of the device they are powering. However, supercapacitors or electric double-layer capacitors, that are nothing more than extremely large value capacitors, cannot come close to the energy density offered by batteries, and suffer from high self-discharge rates, of 30% as compared to 5% encountered in batteries [103], [141]. Modeling the behavior of supercapacitors has important implications for the design of energy harvesting IoT devices [143]. Efficient energy modeling of energy harvesting IoT devices enables the design of optimal energy buffers for achieving uninterrupted operation. This challenge of designing proper energy buffers was previously solved by over-dimensioning [144].

V. CASE STUDY SYSTEMS

In this section, we present two IoT case study systems, in which the sensing devices are fitted with energy harvesting mechanisms helping them achieve energy autonomy. We describe the implementation details of the hardware along with considerations and lessons learned from the corresponding design, implementation, and operation phases. In the first case study, we used solar energy harvesting, while the second case study is based on RF energy harvesting. Both systems use environmental BLE beacons, that operate in an IoT scenario (Figure 8), thus becoming IoT sensing devices [50], [126]. Beacons are a class of wireless sensing systems that only transmit data to base stations which can be fixed or mobile [115]. The IoT devices in the two case studies (monitoring systems) broadcast the measured parameters, and BLE-enabled terminals (such as smartphones) receive this data. The smartphones running monitoring applications relay the data to the cloud through Internet links. Using cloud computing resources, we can perform data processing, visualization, and prediction on the data stored in the cloud.

A. SOLAR-POWERED ENVIRONMENTAL BLE BEACON

1) CASE STUDY SYSTEM OVERVIEW

BLE is a wireless communication technology [145] that is being increasingly used in IoT applications because of its simplicity, ubiquity in most current electronic devices, and low power operation [146], [147]. Applications such as retail [124], environmental monitoring [125], indoor localization [148], museum guiding [149], or inventory management [150] are using BLE beacons. The IoT sensor device presented in [126] measures light intensity, temperature, and relative humidity of the environment. We have described the advantages and limitations posed by BLE devices advertising the acquired data to nearby monitoring applications in general and of this device in particular in our previous work [126].

TABLE 2. Summary of Energy Harvesting Models.

Energy source	Architecture of IoT device with energy harvesting characteristics	Approach	Goals and results
Solar [128, 129]	Harvest-Store-Use	Deterministic model (scheduling schemes)	- Maximization of data rate - Dimensioning of the energy storage element
Solar and wind [130]	Harvest-Store-Use	Deterministic model (scheduling schemes)	- Optimal scheduling scheme to establish the overall power consumption policy based on the utility and on the energy required by tasks
Generally applied [135]	Harvest-Store-Use	Markov model	- Performance evaluation of energy harvesting IoT devices in terms of the device configuration (capacitance and turn-on voltage threshold), application behavior (data transmission interval, data packet size) and environmental conditions (energy harvesting rate)
RF [136]	Harvest-Store-Use	Gamma process Renewal reward theory	- Mathematical model for storage energy policy - Optimal transmission policy
Hybrid [137]	Harvest-Store-Use, hybrid energy harvesting IoT device	Gaussian Mixture model	- Predictability of energy harvesting parameters - Simple design, dimensioning and performance evaluation of energy harvesting IoT devices
Generally applied [138]	Energy harvesting user equipment that includes batteries	Reinforcement learning methods	- Optimal control policy for access control and continuous power control
Solar and human heat [139]	Harvest-Store-Use	Kalman Filter based model	- Energy harvesting platform for human activity and environmental monitoring - Prediction model of the amount of harvested energy

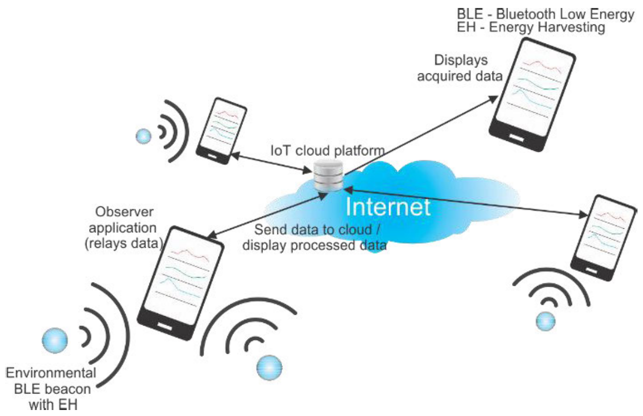


FIGURE 8. IoT scenario for use-case systems' operation. Adapted from [50], [126].

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 energy-efficient autonomous operation of the IoT device.

2) HARDWARE ARCHITECTURE

The architecture of the IoT device consists of a programmable BLE-enabled radio on chip component, the Cypress Semiconductor EZ-BLE PRoC Module [152], an SHT21 temperature (T) and relative humidity (RH) sensor [153], an MPL115A2, absolute pressure (P) sensor [154], and a PT3001 digital ambient light sensor [155]. The power source includes a bq25504 ultra low-power boost converter with battery management for energy harvesting applications [156], two IXYS KXOB22-04 $\times$ 3L amorphous silicon solar cells connected in series [157], a single-cell coin rechargeable battery (accumulator) [158], and two TPS78330DDCT low-dropout linear regulators (LDOs) [159]. Figure 9 shows theses various components and Figure 10 shows the integrated hardware. As the solar energy source cannot be controlled, the device is built using a generate-store-use architecture, where a rechargeable battery stores the energy that is subsequently supplied to the electronics of the device.

To enable better control over the power consumption of the device, two TPS78330DDCT Low-DropOut linear regulators (LDOs) were used for providing power to the processing and sensing parts of the device. Therefore, the firmware can control the power source for both the central part of the device and the sensing component. As the beacon periodically samples the sensors in its structure, processes the acquired data, and broadcasts it, the sensors' power supply can be switched off between readings so that the overall power consumption of the system can be minimized.

3) OPTIMIZATIONS FOR ACHIEVING ENERGY AUTONOMY AND RESULTS

Our initial work has shown that the BLE beacon can achieve energy autonomy without requiring advanced power-optimization techniques when the gas sensor is not operational [126]. The setting of the processor's clock frequency to a value of 3 MHz, the readings of the attached sensors (T, RH, P, light) once every minute, and the transmission of an advertisement every 3 s resulted in a 37 μA

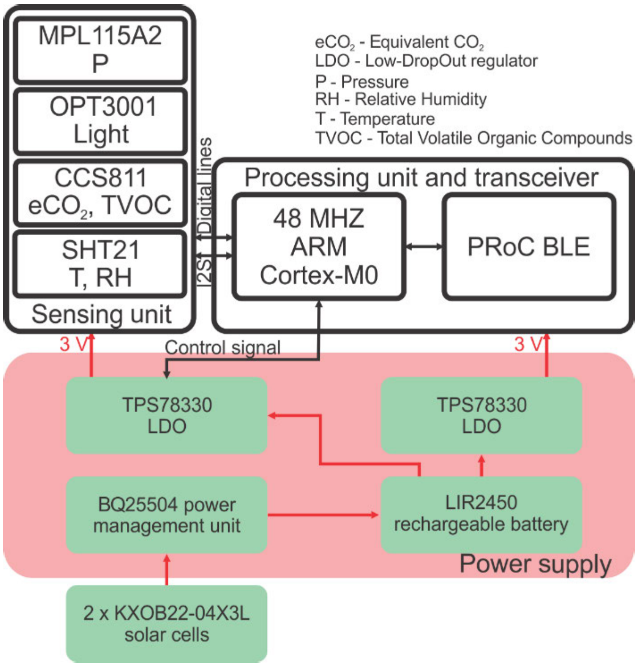


FIGURE 9. Architecture of solar-powered BLE beacon [50], [126] .

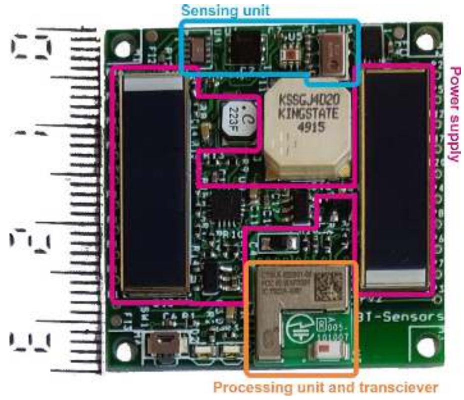


FIGURE 10. Manufactured solar-powered BLE beacon (CCS811 not populated).

average current drawn by the device. This value is sufficiently low to allow stand-alone operation, with the solar cells being capable of charging the accumulator within a single day with good weather. In this scenario, the sensors are powered only once a minute, when they are read, and the resulting data is used to update the advertisement packet. The control module spends almost all the time in sleep mode and wakes up once every three seconds for 3 ms to transmit the advertisement packet, and 140 ms every minute for communicating with the attached sensors.

The addition of the CCS811 gas sensor in the design of the IoT device for providing data regarding the eCO_2 (equivalent CO_2) and Total Volatile Organic Compounds (TVOC) levels in the air required the use of more complex mechanisms for achieving autonomy from an energy perspective [50]. These firmware optimization mechanisms were needed because of the higher power consumption and requirement for longer wake-up periods of the gas sensor. We implemented adaptive duty-cycling strategies in the design of the firmware running on the IoT device considering the light intensity and the amount of energy stored in the accumulator. We incorporate these strategies to lower the overall power consumption of the IoT device. Furthermore, the advertising interval also had to be increased for reducing the overall energy consumption of the IoT device. Thus, we used an interval of 5 s instead of the previous 3 s interval. The IoT device consumes more energy when the attached sensors are active and take measurements than when the transmission of advertisements of the collected data takes place. Therefore, the sensors in the structure of the IoT device are sampled with different rates, depending on their power consumption and on the voltage value estimated for the rechargeable battery and as well on the light intensity. Thus, the T, RH, and the light intensity sensors are powered up and read every minute, when the battery voltage is also measured and computed using a special circuit in the design as described in [50]. If the intensity of light and the battery level are above some thresholds, the wake-up period is prolonged, and the gas sensor performs the reading operation. Otherwise, the reading of the CCS811 sensor is postponed until a future wake-up period with favorable conditions (battery level and light intensity are above previously set thresholds) takes place. By choosing appropriate values for the thresholds and for the maximum number of delay periods for the reading of the gas sensor, efficient activity planning that enables energy autonomy can be reached despite unfavorable weather conditions (presence of clouds) and of the day/night cycle, as the results in [50] have shown. We achieve this result by carefully dimensioning (size of the solar cells in the structure of the IoT device) the energy harvesting circuits and by efficient hardware and software designs (separate power source for the sensors, battery level measurement circuit, adaptive duty-cycling strategy).

B. RF ENERGY HARVESTING ENVIRONMENTAL BLE BEACON

1) CASE STUDY SYSTEM OVERVIEW

In the second use case system, we replaced the power source of the BLE beacon by an RF energy harvesting element as Figure 11 shows. The IoT device in this case is also based on a harvest-store-use architecture. Figure 11 shows the block diagram of the system [4].

The resulting IoT device operates in a similar way as the previous system we have described in the previous section. However, due to the smaller amounts of scavenged energy using RF harvesting elements, it was not possible to power on the CCS811 gas sensor. Since the generated energy cannot sustain the operation of the CCS811 gas sensors, the RF energy harvesting BLE beacon presented can measure T, RH, light intensity, and atmospheric pressure.

2) HARDWARE ARCHITECTURE

As Figure 11 shows, the power supply of the first use case system was replaced by an RF energy harvesting circuit

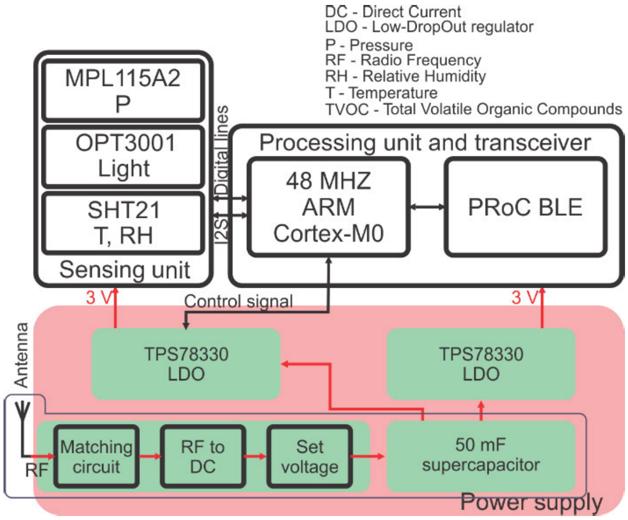


FIGURE 11. Architecture of RF-powered BLE beacon [4].

that charges a supercapacitor. Since the CCS811 gas sensor requires energy levels that cannot be provided by the energy harvesting circuit and longer wakeup periods, it was removed from the IoT device. The power supply consists of a P1110 Powerharvester charging module [160], to which a 50 mF capacitor is connected for storing the generated energy. The P1110 evaluation board generates energy from signals having frequencies in the range of 850–950 MHz and charges the on-board supercapacitor powering the BLE-enabled IoT device. Although a capacitor assuring many charging-discharging cycles is used instead of a rechargeable battery, it suffers from having high leakage current, with values (5–10 μA) comparable to the sleep current ($\sim$1–10 μA) of wireless sensor nodes. In the setup presented here, the 50 mF capacitor discharges itself from 3.3 V to 2.3 V in less than 5 hours. A Global System for Mobile Communications (GSM) phone operating within a band close to the one required by the P1110 module (2G technology) placed at 5 cm from the harvester antenna is able to charge the capacitor to 3.3 V in less than three minutes. By knowing these values and the energy profile of the powered IoT device, an estimation of the rate at which the energy harvesting mechanism should charge the energy storage element can be computed, and adjustments to the design of the entire system can be performed. We have presented a detailed description of the design and the experimental results obtained in [4].

3) OPTIMIZATIONS FOR ACHIEVING ENERGY AUTONOMY AND RESULTS

The firmware on the IoT device implements a simple duty-cycled system where the attached sensors are read every 30 seconds and the advertisement period is set to 3 seconds. Since we wanted to test the feasibility of using RF energy harvesting for such a system, no other optimizations were performed on the application running on the central unit of the IoT device. Our experimental results demonstrated that the 30 cm^2 antenna of the P1110 RF Powerharvester can deliver the power required by the IoT device that samples the attached sensors every half minute and sends an advertisement packet every 3 seconds, when a 2G GSM phone closer than 10 cm is in an active call. However, this was made possible after finding the optimal distance between the energy source and the energy harvesting component and the proper alignment between the two. The supercapacitor in the design is another challenge because of its high self-discharge current, and should be replaced by other, more efficient, energy storage elements. Another challenge when designing such circuits is represented by the efficient measurement of the signals involved. For example, the current drawn by the BLE beacon varies in a very short amount of time between microamperes and tens or hundreds of milliamperes. This quick variation requires measurement equipment with wide input ranges and large sampling rates. However, probably the biggest challenge when designing RF energy harvesting IoT devices is in the miniaturization of the hardware. IoT-enabled sensors should have small form factors and should be low cost, while better RF energy systems require larger antennas and more complex circuitry. Although the work presented in [4] demonstrated that RF energy harvesting could generate enough power for certain IoT devices, this is possible only when specific conditions (such as an active source in the immediate proximity of the system, signal in the frequency range required by the harvester) are met.

C. 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.

1) HARDWARE

The hardware design of the two case study systems demonstrated that significant energy savings can be achieved by using simple methods. One is the use of a separate power source for the sensors attached to the IoT device. This way, the software has control over the operation of the sensors and can efficiently schedule their active periods. This design feature enabled the solar powered IoT device to adapt the reading of the attached sensors depending on the amount of energy generated and on the level of the accumulator.

Another useful energy saving feature is the lowering of the operational frequency of the microcontroller. The frequency value should be close to the one that makes the static component of the current drawn by the IoT device the main consumer, and not the dynamic one. Reducing the operating frequency from 48 MHz to 12 MHz did not significantly increase the data processing time, but considerably lowered the power consumption.

2) ENERGY HARVESTER

There is a category of energy harvesting methods which can provide sufficient energy for prolonged periods of time and also offer the advantage of miniaturization. These include solar cells and piezoelectric circuits. On the other hand, there are energy harvesting mechanisms that generate small amounts of energy at discrete moments in time, while also occupying more space. An example of such a method is RF energy harvesting. This represents a major challenge in the development of energy harvesting IoT devices, since these must be small and based on simple designs. Currently, these requirements seem to be fulfilled in a more facile way by the first category of energy harvesting mechanisms (solar cells and piezoelectric circuits). One option for using RF energy harvesting could be to embed the antenna into objects such as clothes in the case of wearable IoT devices.

An energy budget of between 50 and 60 μAh generated by an energy harvesting circuit could assure autonomous operation from an energy perspective, without the need of using a battery as the main power supply, for a wide range of IoT devices. Given that we expect billions of IoT devices deployed in coming years, energy harvesting could provide significant savings in terms of energy and of materials and efforts used for the manufacturing and disposal of batteries.

3) SOFTWARE

Algorithms for optimizing the energy consumption can overcome problems such as the non-controllability of the energy source. The firmware developed for the first use case system, that generates energy from sunlight, manages to adapt the operation of the IoT device and reduce the energy used during periods when the conditions are not favorable (cloudy weather, nighttime, small amount of energy stored in the accumulator). Software plays a major role in the prediction of harvested energy in the case of solar energy, while in the case of RF energy harvesting, hardware seems to be more important in optimizing the operation of the IoT device. The use of an algorithm for selectively sending data depending on its variation (i.e., send more rarely slow changing data) would increase energy efficiency in both cases.

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.

VI. 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 modeling***. 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.

VII. CONCLUSION

Energy harvesting has been receiving a lot of attention by various research communities and industry involved in the design and implementation of self-powered IoT devices. In this article, we analyzed the energy harvesting technologies used primarily in the IoT environment. We conclude that some energy harvesting technologies can provide a significant amount of energy for a long time using small size PV cells or piezoelectric devices. In contrast, other energy harvesting techniques provide a small amount of energy at discrete moments of time and require large circuits for capturing the energy, but they do not depend on certain cycles such as day/night, working days/weekends, nor are they easy to shield (i.e., RF). The appropriate energy harvesting technique depends mainly on the parameter to be measured, the use case scenario of the IoT device (fixed/mobile, surface/built-in), but also on its location (indoor/outdoor). To demonstrate the potential of solar and RF energy sources, we described two IoT case study systems from our previous work with harvesting mechanisms in terms of their design, hardware implementation and operation. Finally, we have discussed some future technical challenges, whose addressing will facilitate the large-scale deployment of energy harvesting solutions for IoT.

LIST OF ACRONYMS

AES	Advanced Encryption Standard
AI	Artificial Intelligence
ARQ	Automatic Repeat Request
BLE	Bluetooth Low Energy
BSN	Body Sensor Node
DC	Direct Current
DES	Data Encryption Standard
DVS	Dynamic Voltage Scaling
ECG	ElectroCardioGram
eCO2	Equivalent CO2
EEG	ElectroEncephaloGram
EH	Energy Harvesting
EMEH	ElectroMagnetic Energy Harvester
EMG	ElectroMyoGram
ESEH	ElectroStatic Energy Harvester
grms	Root Mean Square acceleration
GSM	Global System for Mobile Communications
ICs	Integrated Circuits
ICTs	Information and Communication Technologies
IoT	Internet of Things
IP	Internet Protocol
ITU	International Telecommunications Union
LDOs	Low-DropOut linear regulators
MAC	Medium Access Control
MAPE	Mean Absolute Percentage Error
MCU	MicroController Unit
MPPT	Maximum Power Point Tracking
P	Pressure
PEEH	PyroElectric Energy Harvester
PEH	Piezoelectric Energy Harvester

PLL	software Phase Locked Loops
PV	PhotoVoltaic
QoS	Quality of Service
RAM	Random Access Memory
RF	Radio Frequency
RFEH	RF Energy Harvester
RH	Relative Humidity
RSA	Rivest, Shamir, and Adelman
T	Temperature
TEEH	ThermoElectric Energy Harvester
TVOC	Total Volatile Organic Compounds
UDP	User Datagram Protocol
WSNs	Wireless Sensor Networks

REFERENCES

[1] *ITU Internet Reports 2005: The Internet of Things, Executive Summary*, Int. Telecommun. Union (ITU), Geneva, Switzerland, Nov. 2005.

[2] K. L. Lueth. (Nov. 19, 2020). *State of the IoT 2020*. Accesssed: Dec. 29, 2020. [Online]. Available: https://iot-analytics.com/state-of-the-iot-2020-12-billion-iot-connections-surpassing-non-iot-for-the-first-time/

[3] Y. Khan. (Apr. 21, 2020). *5 Essential Components of an IoT Ecosystem*. Accessed: Nov. 11, 2020. [Online]. Available: https://learn.g2.com/iot-ecosystem

[4] T. Sanislav, S. Zeadally, G. D. Mois, and S. C. Folea, "Wireless energy harvesting: Empirical results and practical considerations for Internet of Things," *J. Netw. Comput. Appl.*, vol. 121, pp. 149–158, Nov. 2018.

[5] S. Zeadally, A. Das, and N. Sklavos, "Cryptographic technologies and protocol standards for Internet of Things," *Internet Things, Eng. Cyber Phys. Hum. Syst.*, to be published. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S2542660519301799

[6] A. K. Das, S. Zeadally, and D. He, "Taxonomy and analysis of security protocols for Internet of Things," *Future Gener. Comput. Syst.*, vol. 89, pp. 110–125, Dec. 2018.

[7] R. Yugha and S. Chithra, "A survey on technologies and security protocols: Reference for future generation IoT," *J. Netw. Comput. Appl.*, vol. 169, Nov. 2020, Art. no. 102763.

[8] J.-M. Dilhac and V. Boitier, "Wireless sensor networks," in *Energy Autonomy of Batteryless and Wireless Embedded Systems*, J. Dilhac and V. Boitier, Eds. Amsterdam, The Netherlands: Elsevier, 2016, ch. 1, pp. 1–11.

[9] E. Suganya, S. Sountharrajan, K. S. Shandilya, and M. Karthiga, "IoT in agriculture investigation on plant diseases and nutrient level using image analysis techniques," in *Internet of Things in Biomedical Engineering*, V. E. Balas, L. H. Son, S. Jha, M. Khari, and R. Kumar, Eds. New York, NY, USA: Academic, 2019, ch. 5, pp. 117–130.

[10] T. Sanislav, G. Mois, S. Folea, and L. Miclea, "Integrating wireless sensor networks and cyber-physical systems: Challenges and opportunities," in *Cyber-Physical System Design With Sensor Networking Technologies* (Control, Robotics and Sensors). Edison, NJ, USA: IET, 2016, pp. 47–76.

[11] O. Bello and S. Zeadally, "Toward efficient smartification of the Internet of Things (IoT) services," *Future Gener. Comput. Syst.*, vol. 92, pp. 663–673, Mar. 2019.

[12] M. T. Lazarescu, "Wireless sensor networks for the Internet of Things: Barriers and synergies," in *Components and Services for IoT Platforms*, G. Keramidas, N. Voros, and M. Hübner, Eds. Cham, Switzerland: Springer, 2017, doi: 10.1007/978-3-319-42304-3_9.

[13] P. S. Mathew, A. S. Pillai, and V. Palade, "Applications of IoT in healthcare," in *Cognitive Computing for Big Data Systems Over IoT* (Lecture Notes on Data Engineering and Communications Technologies), vol. 14, A. Sangaiah, A. Thangavelu, and V. M. Sundaram, Eds. Cham, Switzerland: Springer, 2018, doi: 10.1007/978-3-319-70688-7_11.

[14] K. Haseeb, I. U. Din, A. Almogren, and N. Islam, "An energy efficient and secure IoT-based WSN framework: An application to smart agriculture," *Sensors*, vol. 20, no. 7, p. 2081, Apr. 2020, doi: 10.3390/s20072081.

[15] B. Hammi, R. Khatoun, S. Zeadally, A. Fayad, and L. Khoukhi, "Internet of Things (IoT) Technologies for Smart Cities," *IET Netw.*, vol. 7, no. 1, pp. 1–16, 2018.

[16] M. Jia, A. Komeily, Y. Wang, and R. S. Srinivasan, "Adopting Internet of Things for the development of smart buildings: A review of enabling technologies and applications," *Autom. Construct.*, vol. 101, pp. 111–126, May 2019, doi: 10.1016/j.autcon.2019.01.023.

[17] C. Yang, W. Shen, and X. Wang, "The Internet of Things in manufacturing: Key issues and potential applications," *IEEE Syst., Man, Cybern. Mag.*, vol. 4, no. 1, pp. 6–15, Jan. 2018, doi: 10.1109/MSMC.2017.2702391.

[18] J. Contreras-Castillo, S. Zeadally, and J. Guerrero, "Sensor technologies for intelligent transportation systems," *Sensors*, vol. 18, no. 4, p. 212, 2018.

[19] L. Muduli, D. P. Mishra, and P. K. Jana, "Application of wireless sensor network for environmental monitoring in underground coal mines: A systematic review," *J. Netw. Comput. Appl.*, vol. 106, pp. 48–67, Mar. 2018.

[20] R. Vera-Amaro, M. E. R. Angeles, and A. Luviano-Juarez, "Design and analysis of wireless sensor networks for animal tracking in large monitoring polar regions using phase-type distributions and single sensor model," *IEEE Access*, vol. 7, pp. 45911–45929, 2019.

[21] M. Farsi, M. A. Elhosseini, M. Badawy, H. A. Ali, and H. Z. Eldin, "Deployment techniques in wireless sensor networks, coverage and connectivity: A survey," *IEEE Access*, vol. 7, pp. 28940–28954, 2019.

[22] J. Gabay. (Mar. 27, 2014). *Wireless Links Inside Rotating Machinery*. Digi-Key Electronics. Accessed: Dec. 23, 2020. [Online]. Available: https://www.digikey.com/en/articles/wireless-links-inside-rotating-machinery

[23] M. Hulea, G. Mois, S. Folea, L. Miclea, and V. Biscu, "Wi-sensors: A low power Wi-Fi solution for temperature and humidity measurement," in *Proc. IECON-39th Annu. Conf. IEEE Ind. Electron. Soc.*, Vienna, Austria, Nov. 2013, pp. 4011–4015, doi: 10.1109/IECON.2013.6699777.

[24] F. Shaikh and S. Zeadally, "Energy harvesting in wireless sensor networks: A comprehensive survey," *Renew. Sustain. Energy Rev.*, vol. 55, pp. 1041–1054, Mar. 2016.

[25] S. Ma, M. Jiang, P. Tao, C. Song, J. Wu, J. Wang, T. Deng, and W. Shang, "Temperature effect and thermal impact in lithium-ion batteries: A review," *Prog. Natural Sci., Mater. Int.*, vol. 28, no. 6, pp. 653–666, 2018.

[26] Texas Instruments Incorporated, Dallas, TX, USA. (Apr. 2020). *Using Input Current Limiting to Extend Battery Life*. Accessed: Dec. 23, 2020. [Online]. Available: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwid_J7kkuTtAhWnAxAIHcn4CMMQFjAJegQIHBAC&url=http%3A%2F%2Fwww.ti.com%2Flit%2Fpdf%2FSLVAES7&usg=AOvVaw1EWJ0-zYdgxGJUzt9CUhUC

[27] A. Dionisi, D. Marioli, E. Sardini, and M. Serpelloni, "Autonomous wearable system for vital signs measurement with energy-harvesting module," *IEEE Trans. Instrum. Meas.*, vol. 65, no. 6, pp. 1423–1434, Jun. 2016.

[28] Perchards, Hertfordshire, United Kingdom. (Dec. 2016). *The Collection of Waste Portable Batteries in Europe in View of the Achievability of the Collection Targets Set by Batteries Directive 2006/66/EC*. Accessed: Dec. 23, 2020. [Online]. Available: https://www.epbaeurope.net/wp-content/uploads/2016/12/Reportontheportablebatterycollectionrates-UpdateDec-15-ExerptofChanges.pdf

[29] R. Atat, L. Liu, J. Wu, G. Li, C. Ye, and Y. Yang, "Big data meet cyber-physical systems: A panoramic survey," *IEEE Access*, vol. 6, pp. 73603–73636, 2018.

[30] N. Soin, "Magnetic nanoparticles—Piezoelectric polymer nanocomposites for energy harvesting," in in *In Micro and Nano Technologies, Magnetic Nanostructured Materials*. Amsterdam, The Netherlands: Elsevier, 2018, ch. 10, pp. 295–322.

[31] D. Altinel and G. K. Kurt, "Modeling of hybrid energy harvesting communication systems," *IEEE Trans. Green Commun. Netw.*, vol. 3, no. 2, pp. 523–534, Jun. 2019.

[32] S. Sudevalayam and P. Kulkarni, "Energy harvesting sensor nodes: Survey and implications," *IEEE Commun. Surveys Tuts.*, vol. 13, no. 3, pp. 443–461, 3rd Quart., 2011.

[33] C. S. Psomopoulos, "Solar energy: Harvesting the sun's energy for sustainable future," in *Handbook of Sustainable Engineering*, J. Kauffman and K. Lee, Eds. Dordrecht, The Netherlands: Springer, 2013, pp. 1065–1107.

[34] P. Breeze, "Solar power," in *Power Generation Technologies*, P. Breeze, Ed., 3rd ed. Oxford, U.K.: Newnes, 2019, ch. 13, pp. 293–321.

[35] P. Saini, D. V. Patil, and S. Powar, "Review on integration of solar air heaters with thermal energy storage," in *Applications of Solar Energy. Energy, Environment, and Sustainability*, H. Tyagi, A. Agarwal, P. Chakraborty, and S. Powar, Eds. Singapore: Springer, 2018, pp. 163–186.

[36] M. Prauzek, J. Konecny, M. Borova, K. Janosova, J. Hlavica, and P. Musilek, "Energy harvesting sources, storage devices and system topologies for environmental wireless sensor networks: A review," *Sensors*, vol. 18, no. 2446, pp. 1–22, 2018.

[37] H. Wei, H. Zhang, H. Sun, and B. Yang, "Preparation of polymer–nanocrystals hybrid solar cells through aqueous approaches," *Nano Today*, vol. 7, no. 4, pp. 316–326, Aug. 2012.

[38] J. Yick, B. Mukherjee, and D. Ghosal, "Wireless sensor network survey," *Comput. Netw.*, vol. 52, no. 12, pp. 1286–1389, 2008.

[39] Y. Wang, P. Luo, X. Zeng, D. Peng, Z. Li, and B. Zhang, "A neural network assistance AMPPT solar energy harvesting system with 89.39% efficiency and 0.01–0.5% tracking errors," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 67, no. 9, pp. 2960–2971, Sep. 2020.

[40] S. H. Cheong, M. Kang, Y. Kim, M. Park, J. Park, and D. K. Noh, "Solar-CTP: An enhanced CTP for solar-powered wireless sensor networks," *IEEE Access*, vol. 8, pp. 127142–127155, 2020.

[41] C. Wang, J. Li, Y. Yang, and F. Ye, "Combining solar energy harvesting with wireless charging for hybrid wireless sensor networks," *IEEE Trans. Mobile Comput.*, vol. 17, no. 3, pp. 560–576, Mar. 2018.

[42] J. Mohtasham, "Review article-renewable energies," *Energy Procedia*, vol. 74, pp. 1289–1297, Aug. 2015.

[43] M. Kumar, "Enhanced solar PV power generation under PSCs using shade dispersion," *IEEE Trans. Electron Devices*, vol. 67, no. 10, pp. 4313–4320, Oct. 2020.

[44] Q. Liu and Q.-J. Zhang, "Accuracy improvement of energy prediction for solar-energy-powered embedded systems," *IEEE Trans. Very Large Scale Integr. (VLSI) Syst.*, vol. 24, no. 6, pp. 2062–2074, Jun. 2016.

[45] M. Hassan and A. Bermak, "Solar harvested energy prediction algorithm for wireless sensors," in *Proc. 4th Asia Symp. Qual. Electron. Design (ASQED)*, Penang, Malaysia, Jul. 2012, pp. 178–181, doi: 10.1109/ACQED.2012.6320497.

[46] F. A. Kraemer, D. Palma, A. E. Braten, and D. Ammar, "Operationalizing solar energy predictions for sustainable, autonomous IoT device management," *IEEE Internet Things J.*, vol. 7, no. 12, pp. 11803–11814, Dec. 2020.

[47] J. Gruetter. (Oct. 2010). *Solar Energy Harvesting—Low Power in a Compact Footprint*. Accessed: Jan. 3, 2021. [Online]. Available: https://www.powersystemsdesign.com/articles/solar-energy-harvesting/22/5742

[48] Y. Wu, C. Li, Z. Tian, and J. Sun, "Solar-driven integrated energy systems: State of the art and challenges," *J. Power Sources*, vol. 478, Dec. 2020, Art. no. 228762.

[49] H. Akinaga, "Recent advances and future prospects in energy harvesting technologies," *Jpn. J. Appl. Phys.*, vol. 59, no. 11, Nov. 2020, Art. no. 110201.

[50] G. Mois, T. Sanislav, S. Folea, and S. Zeadally, "Performance evaluation of energy-autonomous sensors using power-harvesting beacons for environmental monitoring in Internet of Things (IoT)," *Sensors*, vol. 18, no. 6, p. 1709, 2018.

[51] X. Liu and E. Sanchez-Sinencio, "A highly efficient ultralow photovoltaic power harvesting system with MPPT for Internet of Things smart nodes," *IEEE Trans. Very Large Scale Integr. (VLSI) Syst.*, vol. 23, no. 12, pp. 3065–3075, Dec. 2015.

[52] F. Wu, J.-M. Redoute, and M. R. Yuce, "WE-safe: A self-powered wearable IoT sensor network for safety applications based on LoRa," *IEEE Access*, vol. 6, pp. 40846–40853, 2018.

[53] G. Mois, Z. Szilagyi, T. Sanislav, and S. Folea, "An HTTP-based environmental monitoring system using power harvesting," in *Proc. 21st Int. Conf. Syst. Theory, Control Comput. (ICSTCC)*, Sinaia, Balkans, Oct. 2017, pp. 845–848, doi: 10.1109/ICSTCC.2017.8107142.

[54] C. Yang, R. Xue, X. Li, X. Zhang, and Z. Wu, "Power performance of solar energy harvesting system under typical indoor light sources," *Renew. Energy*, vol. 161, pp. 836–845, Dec. 2020.

[55] S. Biswas, Y.-J. You, Y. Lee, J. W. Shim, and H. Kim, "Efficiency improvement of indoor organic solar cell by optimization of the doping level of the hole extraction layer," *Dyes Pigments*, vol. 183, Dec. 2020, Art. no. 108719.

[56] C. S. Abella, S. Bonina, A. Cucuccio, S. D'Angelo, G. Giustolisi, A. D. Grasso, A. Imbruglia, G. S. Mauro, G. A. M. Nastasi, G. Palumbo, S. Pennisi, G. Sorbello, and A. Scuderi, "Autonomous energy-efficient wireless sensor network platform for home/office automation," *IEEE Sensors J.*, vol. 19, no. 9, pp. 3501–3512, May 2019, doi: 10.1109/JSEN.2019.2892604.

[57] T. V. Tran and W.-Y. Chung, "High-efficient energy harvester with flexible solar panel for a wearable sensor device," *IEEE Sensors J.*, vol. 16, no. 24, pp. 9021–9028, Dec. 2016.

[58] D. Newell and M. Duffy, "Demonstrating the scope of a switched supercapacitor circuit for energy harvesting powered wireless sensor loads," *IEEE Trans. Power Electron.*, vol. 34, no. 8, pp. 7532–7541, Aug. 2019.

[59] R. A. Kjellby, T. E. Johnsrud, S. E. Loetveit, L. R. Cenkeramaddi, M. Hamid, and B. Beferull-Lozano, "Self-powered IoT device for indoor applications," in *Proc. 31st Int. Conf. VLSI Design 17th Int. Conf. Embedded Syst. (VLSID)*, Pune, India, Jan. 2018, pp. 455–456, doi: 10.1109/VLSID.2018.110.

[60] M. Hassanalieragh, T. Soyata, A. Nadeau, and G. Sharma, "UR-SolarCap: An open source intelligent auto-wakeup solar energy harvesting system for supercapacitor-based energy buffering," *IEEE Access*, vol. 4, pp. 542–557, 2016.

[61] L.-G. Tran, H.-K. Cha, and W.-T. Park, "RF power harvesting: A review on designing methodologies and applications," *Micro Nano Syst. Lett.*, vol. 5, no. 1, pp. 1–16, Dec. 2017, doi: 10.1186/s40486-017-0051-0.

[62] M. Cansiz, D. Altinel, and G. K. Kurt, "Efficiency in RF energy harvesting systems: A comprehensive review," *Energy*, vol. 174, pp. 292–309, May 2019, doi: 10.1016/j.energy.2019.02.100.

[63] O. Assogba, A. K. Mbodji, and A. Karim Diallo, "Efficiency in RF energy harvesting systems: A comprehensive review," in *Proc. IEEE Int. Conf Natural Eng. Sci. Sahel's Sustain. Develop.-Impact Big Data Appl. Soc. Environ. (IBASE-BF)*, Ouagadougou, Burkina Faso, Feb. 2020, pp. 1–10, doi: 10.1109/IBASE-BF48578.2020.9069597.

[64] N. A. Eltresy, O. M. Dardeer, A. Al-Habal, E. Elhariri, A. H. Hassan, A. Khattab, D. N. Elsheakh, S. A. Taie, H. Mostafa, H. A. Elsadek, and E. A. Abdallah, "RF energy harvesting IoT system for museum ambience control with deep learning," *Sensors*, vol. 19, no. 20, p. 4465, Oct. 2019.

[65] M. Caselli, M. Ronchi, and A. Boni, "Power management circuits for low-power RF energy harvesters," *J. Low Power Electron. Appl.*, vol. 10, no. 3, p. 29, Sep. 2020.

[66] C.-H. Lin, C.-W. Chiu, and J.-Y. Gong, "A wearable rectenna to harvest low-power RF energy for wireless healthcare applications," in *Proc. 11th Int. Congr. Image Signal Process., Biomed. Eng. Informat. (CISP-BMEI)*, Beijing, China, Oct. 2018, pp. 1–5, doi: 10.1109/CISP-BMEI.2018.8633222.

[67] A. Dhungana and E. Bulut, "Opportunistic wireless crowd charging of IoT devices from smartphones," in *Proc. 16th Int. Conf. Distrib. Comput. Sensor Syst. (DCOSS)*, Marina del Rey, CA, USA, May 2020, pp. 376–380, doi: 10.1109/DCOSS49796.2020.00066.

[68] A. Dhungana and E. Bulut, "Energy balancing in mobile opportunistic networks with wireless charging: Single and multi-hop approaches," *Ad Hoc Netw.*, vol. 111, Feb. 2021, Art. no. 102342.

[69] N. Elvin and A. Erturk, "Introduction and methods of mechanical energy harvesting," in *Advances in Energy Harvesting Methods*, N. Elvin and A. Erturk, Eds. New York, NY, USA: Springer, 2013, doi: 10.1007/978-1-4614-5705-3_1.

[70] A. Nechibvute, A. Chawanda, and P. Luhanga, "Piezoelectric energy harvesting devices: An alternative energy source for wireless sensors," *Smart Mater. Res.*, vol. 2012, pp. 1–13, May 2012, doi: 10.1155/2012/853481.

[71] H. Li, C. Tian, and Z. D. Deng, "Energy harvesting from low frequency applications using piezoelectric materials," *Appl. Phys. Rev.*, vol. 1, no. 4, Dec. 2014, Art. no. 041301, doi: 10.1063/1.4900845.

[72] H. Elahi, M. Eugeni, and P. Gaudenzi, "A review on mechanisms for piezoelectric-based energy harvesters," *Energies*, vol. 11, no. 7, p. 1850, Jul. 2018.

[73] H. Elahi, K. Munir, M. Eugeni, S. Atek, and P. Gaudenzi, "Energy harvesting towards self-powered IoT devices," *Energies*, vol. 13, no. 21, p. 5528, Oct. 2020.

[74] C. Covaci and A. Gontean, "Piezoelectric energy harvesting solutions: A review," *Sensors*, vol. 20, no. 12, p. 3512, Jun. 2020.

[75] J. Y. Cho, K.-B. Kim, W. S. Hwang, C. H. Yang, J. H. Ahn, S. D. Hong, D. H. Jeon, G. J. Song, C. H. Ryu, S. B. Woo, J. Kim, T. H. Lee, J. Y. Choi, H. Cheong, and T. H. Sung, "A multifunctional road-compatible piezoelectric energy harvester for autonomous driver-assist LED indicators with a self-monitoring system," *Appl. Energy*, vol. 242, pp. 294–301, May 2019, doi: 10.1016/j.apenergy.2019.03.075.

[76] S. Bradai, G. Bouattour, S. Naifar, and O. Kanoun, "Electromagnetic energy harvester for battery-free IoT solutions," in *Proc. IEEE 6th World Forum Internet Things (WF-IoT)*, New Orleans, LA, USA, Jun. 2020, pp. 1–5, doi: 10.1109/WF-IoT48130.2020.9221051.

[77] A. Kumar, S. S. Balpande, and S. C. Anjankar, "Electromagnetic energy harvester for low frequency vibrations using MEMS," *Procedia Comput. Sci.*, vol. 79, pp. 785–792, 2016, doi: 10.1016/j.procs.2016.03.104.

[78] F. U. Khan and M. Iqbal, "Electromagnetic bridge energy harvester utilizing Bridge's vibrations and ambient wind for wireless sensor node application," *J. Sensors*, vol. 2018, pp. 1–18, Feb. 2018, doi: 10.1155/2018/3849683.

[79] Y. Naito and K. Uenishi, "Electrostatic MEMS vibration energy harvesters inside of tire treads," *Sensors*, vol. 19, no. 4, p. 890, Feb. 2019.

[80] Y. Lu, F. Cottone, S. Boisseau, F. Marty, D. Galayko, and P. Basset, "Low-frequency and ultra-wideband MEMS electrostatic vibration energy harvester powering an autonomous wireless temperature sensor node," in *Proc. IEEE 29th Int. Conf. Micro Electro Mech. Syst. (MEMS)*, Shanghai, China, Jan. 2016, pp. 33–36, doi: 10.1109/MEMSYS.2016.7421550.

[81] S. Lee, T. Kang, W. Lee, M. M. Afandi, J. Ryu, and J. Kim, "Multifunctional device based on phosphor-piezoelectric PZT: Lighting, speaking, and mechanical energy harvesting," *Sci. Rep.*, vol. 8, no. 1, p. 301, Dec. 2018, doi: 10.1038/s41598-017-18571-9.

[82] M. Zhou, M. S. H. Al-Furjan, J. Zou, and W. Liu, "A review on heat and mechanical energy harvesting from human–principles, prototypes and perspectives," *Renew. Sustain. Energy Rev.*, vol. 82, pp. 3582–3609, Feb. 2018, doi: 10.1016/j.rser.2017.10.102.

[83] R. Riemer and A. Shapiro, "Biomechanical energy harvesting from human motion: Theory, state of the art, design guidelines, and future directions," *J. NeuroEng. Rehabil.*, vol. 8, no. 1, p. 22, 2011, doi: 10.1186/1743-0003-8-22.

[84] Y. Zhang, F. Zhang, Y. Shakhsheer, J. D. Silver, A. Klinefelter, M. Nagaraju, J. Boley, J. Pandey, A. Shrivastava, E. J. Carlson, A. Wood, B. H. Calhoun, and B. P. Otis, "A batteryless 19 μW MICS/ISM-band energy harvesting body sensor node SoC for ExG applications," *IEEE J. Solid-State Circuits*, vol. 48, no. 1, pp. 199–213, Jan. 2013, doi: 10.1109/JSSC.2012.2221217.

[85] V. Leonov, "Thermoelectric energy harvesting of human body heat for wearable sensors," *IEEE Sensors J.*, vol. 13, no. 6, pp. 2284–2291, Jun. 2013, doi: 10.1109/JSEN.2013.2252526.

[86] C. Watkins, B. Shen, and R. Venkatasubramanian, "Low-grade-heat energy harvesting using superlattice thermoelectrics for applications in implantable medical devices and sensors," in *Proc. ICT. 24th Int. Conf. Thermoelectrics*, Clemson, SC, USA, Jun. 2005, pp. 265–267, doi: 10.1109/ICT.2005.1519934.

[87] M. K. Kim, M. S. Kim, S. E. Jo, H. L. Kim, S. M. Lee, and Y. J. Kim, "Wearable thermoelectric generator for human clothing applications," in *Proc. Transducers Eurosensors XXVII,7th Int. Conf. Solid-State Sensors, Actuat. Microsystems (TRANSDUCERS EUROSENSORS XXVII)*, Barcelona, Spain, Jun. 2013, pp. 1376–1379, doi: 10.1109/Transducers.2013.6627034.

[88] H. Liu, Y. Wang, D. Mei, Y. Y. Shi, and Z. Chen, "Design of a wearable thermoelectric generator for harvesting human body energy," in *Wearable Sensors and Robots* (Lecture Notes in Electrical Engineering), vol. 399, C. Yang, G. Virk, and H. Yang, Eds. Singapore: Springer, 2017, doi: 10.1007/978-981-10-2404-7_5.

[89] Y. Chen, Y. Zhang, F. Yuan, F. Ding, and O. G. Schmidt, "A flexible PMN-PT ribbon-based piezoelectric-pyroelectric hybrid generator for human-activity energy harvesting and monitoring," *Adv. Electron. Mater.*, vol. 3, no. 3, Mar. 2017, Art. no. 1600540.

[90] J.-H. Lee, K. Y. Lee, S.-J. Yoon, M. K. Gupta, T. Y. Kim, J. Oh, D.-Y. Lee, C. Ryu, W. J. Yoo, C.-Y. Kang, J.-B. Yoo, and S.-W. Kim, "Highly stretchable piezoelectric-pyroelectric hybrid nanogenerator," *Adv. Mater.*, vol. 26, no. 5, pp. 765–769, Feb. 2014, doi: 10.1002/adma.201303570.

[91] H. Xue, Q. Yang, D. Wang, W. Luo, W. Wang, M. Lin, D. Liang, and Q. Luo, "A wearable pyroelectric nanogenerator and self-powered breathing sensor," *Nano Energy*, vol. 38, pp. 147–154, Aug. 2017, doi: 10.1016/j.nanoen.2017.05.056.

[92] P. D. Mitcheson, E. M. Yeatman, G. K. Rao, A. S. Holmes, and T. C. Green, "Energy harvesting from human and machine motion for wireless electronic devices," *Proc. IEEE*, vol. 96, no. 9, pp. 1457–1486, Sep. 2008, doi: 10.1109/JPROC.2008.927494.

[93] Y.-M. Choi, M. Lee, and Y. Jeon, "Wearable biomechanical energy harvesting technologies," *Energies*, vol. 10, no. 10, p. 1483, Sep. 2017.

[94] M. Cai, Z. Yang, J. Cao, and W.-H. Liao, "Recent advances in human motion excited energy harvesting systems for wearables," *Energy Technol.*, vol. 8, no. 10, Oct. 2020, Art. no. 2000533, doi: 10.1002/ente.202000533.

[95] M. Cai and W.-H. Liao, "High-power density inertial energy harvester without additional proof mass for wearables," *IEEE Internet Things J.*, vol. 8, no. 1, pp. 297–308, Jan. 2021, doi: 10.1109/JIOT.2020.3003262.

[96] J. Zhong, Y. Zhang, Q. Zhong, Q. Hu, B. Hu, Z. L. Wang, and J. Zhou, "Fiber-based generator for wearable electronics and mobile medication," *ACS Nano*, vol. 8, no. 6, pp. 6273–6280, Jun. 2014, doi: 10.1021/nn501732z.

[97] C. Konstantopoulos, E. Koutroulis, N. Mitianoudis, and A. Bletsas, "Converting a plant to a battery and wireless sensor with scatter radio and ultra-low cost," *IEEE Trans. Instrum. Meas.*, vol. 65, no. 2, pp. 388–398, Feb. 2016.

[98] F.-T. Lin, Y.-C. Kuo, J.-C. Hsieh, H.-Y. Tsai, Y.-T. Liao, and H.-C. Lee, "A self-powering wireless environment monitoring system using soil energy," *IEEE Sensors J.*, vol. 15, no. 7, pp. 3751–3758, Jul. 2015.

[99] B. Dong, Q. Shi, Y. Yang, F. Wen, Z. Zhang, and C. Lee, "Technology evolution from self-powered sensors to AIoT enabled smart homes," *Nano Energy*, vol. 79, Jan. 2021, Art. no. 105414.

[100] H. Liu, H. Fu, L. Sun, C. Lee, and E. M. Yeatman, "Hybrid energy harvesting technology: From materials, structural design, system integration to applications," *Renew. Sustain. Energy Rev.*, vol. 137, Mar. 2021, Art. no. 110473.

[101] F. Deng, X. Yue, X. Fan, S. Guan, Y. Xu, and J. Chen, "Multisource energy harvesting system for a wireless sensor network node in the field environment," *IEEE Internet Things J.*, vol. 6, no. 1, pp. 918–927, Feb. 2019.

[102] T. Yamaguchi and S. Hashimoto, "A green battery by pot-plant power," *IEEJ Trans. Electr. Electron. Eng.*, vol. 7, no. 4, pp. 441–442, Jul. 2012, doi: 10.1002/tee.21754.

[103] Murata Manufacturing Co., Ltd., Nagaokakyo, Kyoto. (Dec. 14, 2016). *Sizing Solar Energy Harvesters for Wireless Sensor Networks—Application Note M1002*. Acessed: Feb. 6, 2021. [Online]. Available: https://wireless.murata.com/media/products/apnotes/anm1002.pdf

[104] S. C. Folea and G. Mois, "A low-power wireless sensor for online ambient monitoring," *IEEE Sensors J.*, vol. 15, no. 2, pp. 742–749, Feb. 2015, doi: 10.1109/JSEN.2014.2351420.

[105] Z. Zhang, L. Shu, C. Zhu, and M. Mukherjee, "A short review on sleep scheduling mechanism in wireless sensor networks," in *Quality, Reliability, Security and Robustness in Heterogeneous Systems* (Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering), vol. 234, L. Wang, T. Qiu, and W. Zhao, Eds. Cham, Switzerland: Springer, 2018, doi: 10.1007/978-3-319-78078-8_7.

[106] A. A.-H. Hassan, W. M. Shah, A.-H.-H. Habeb, M. F. I. Othman, and M. N. Al-Mhiqani, "An improved energy-efficient clustering protocol to prolong the lifetime of the WSN-based IoT," *IEEE Access*, vol. 8, pp. 200500–200517, 2020, doi: 10.1109/ACCESS.2020.3035624.

[107] R. Du, L. Gkatzikis, C. Fischione, and M. Xiao, "Energy efficient sensor activation for water distribution networks based on compressive sensing," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 12, pp. 2997–3010, Dec. 2015, doi: 10.1109/JSAC.2015.2481199.

[108] J. Lee, S. Miyoshi, M. Kawaminami, D. Blaauw, D. Sylvester, Y. Zhang, Q. Dong, W. Lim, M. Saligane, Y. Kim, S. Jeong, J. Lim, and M. Yasuda, "A self-tuning IoT processor using leakage-ratio measurement for energy-optimal operation," *IEEE J. Solid-State Circuits*, vol. 55, no. 1, pp. 87–97, Jan. 2020, doi: 10.1109/JSSC.2019.2939890.

[109] C. Zhuo, S. Luo, H. Gan, J. Hu, and Z. Shi, "Noise-aware DVFS for efficient transitions on battery-powered IoT devices," *IEEE Trans. Comput.-Aided Design Integr. Circuits Syst.*, vol. 39, no. 7, pp. 1498–1510, Jul. 2020, doi: 10.1109/TCAD.2019.2917844.

[110] G. Berthou, K. Marquet, T. Risset, and G. Salagnac, "Accurate power consumption evaluation for peripherals in ultra low-power embedded systems," in *Proc. Global Internet Things Summit (GIoTS)*, Dublin, Ireland, Jun. 2020, pp. 1–6, doi: 10.1109/GIOTS49054.2020.9119593.

[111] H. Choi, Y. Koo, and S. Park, "Modeling the power consumption of function-level code relocation for low-power embedded systems," *Appl. Sci.*, vol. 9, no. 11, p. 2354, Jun. 2019, doi: 10.3390/app9112354.
[112] P. P. Priyesh and S. K. Bharti, "Dynamic transmission power control in wireless sensor networks using P-I-D feedback control technique," in *Proc. 9th Int. Conf. Commun. Syst. Netw. (COMSNETS)*, Bengaluru, India, Jan. 2017, pp. 306–313, doi: 10.1109/COMSNETS.2017.7945391.
[113] H. U. Yildiz, B. Tavli, and H. Yanikomeroglu, "Transmission power control for link-level handshaking in wireless sensor networks," *IEEE Sensors J.*, vol. 16, no. 2, pp. 561–576, Jan. 2016, doi: 10.1109/JSEN.2015.2486960.
[114] L. Tan and M. Wu, "Data reduction in wireless sensor networks: A hierarchical LMS prediction approach," *IEEE Sensors J.*, vol. 16, no. 6, pp. 1708–1715, Mar. 2016, doi: 10.1109/JSEN.2015.2504106.
[115] T. Santejudean, S. Folea, and G. Mois, "Analysis of low-power operation for an environmental monitoring beacon," in *Proc. IEEE Int. Conf. Autom., Qual. Test., Robot. (AQTR)*, Cluj-Napoca, Romania, May 2020, pp. 1–5, doi: 10.1109/AQTR49680.2020.9129917.
[116] D. Goldsmith and J. Brusey, "The spanish inquisition protocol," in *Proc. IEEE Sensors*, Waikoloa, HI, USA, Nov. 2010, pp. 2043–2048, doi: 10.1109/ICSENS.2010.5690285.
[117] X. Shi and G. Stromberg, "SyncWUF: An ultra low-power MAC protocol for wireless sensor networks," *IEEE Trans. Mobile Comput.*, vol. 6, no. 1, pp. 115–125, Jan. 2007, doi: 10.1109/TMC.2007.250675.
[118] A. Ikpehai, B. Adebisi, K. M. Rabie, K. Anoh, R. E. Ande, M. Hammoudeh, H. Gacanin, and U. M. Mbanaso, "Low-power wide area network technologies for Internet-of-Things: A comparative review," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 2225–2240, Apr. 2019, doi: 10.1109/JIOT.2018.2883728.
[119] M. Stusek, K. Zeman, P. Masek, J. Sedova, and J. Hosek, "IoT protocols for low-power massive IoT: A communication perspective," in *Proc. 11th Int. Congr. Ultra Mod. Telecommun. Control Syst. Workshops (ICUMT)*, Dublin, Ireland, Oct. 2019, pp. 1–7, doi: 10.1109/ICUMT48472.2019.8970868.
[120] M. S. Bahbahani and E. Alsusa, "A cooperative clustering protocol with duty cycling for energy harvesting enabled wireless sensor networks," *IEEE Trans. Wireless Commun.*, vol. 17, no. 1, pp. 101–111, Jan. 2018, doi: 10.1109/TWC.2017.2762674.
[121] A. Kumar, M. Zhao, K.-J. Wong, Y. L. Guan, and P. H. J. Chong, "A comprehensive study of IoT and WSN MAC protocols: Research issues, challenges and opportunities," *IEEE Access*, vol. 6, pp. 76228–76262, 2018, doi: 10.1109/ACCESS.2018.2883391.
[122] A. Jarwan, A. Sabbah, and M. Ibnkahla, "Data transmission reduction schemes in WSNs for efficient IoT systems," *IEEE J. Sel. Areas Commun.*, vol. 37, no. 6, pp. 1307–1324, Jun. 2019, doi: 10.1109/JSAC.2019.2904357.
[123] Y. Fathy and P. Barnaghi, "Quality-based and energy-efficient data communication for the Internet of Things networks," *IEEE Internet Things J.*, vol. 6, no. 6, pp. 10318–10331, Dec. 2019, doi: 10.1109/JIOT.2019.2938101.
[124] P. Spachos and A. Mackey, "Energy efficiency and accuracy of solar powered BLE beacons," *Comput. Commun.*, vol. 119, pp. 94–100, Apr. 2018.
[125] S. C. Folea and G. D. Mois, "Lessons learned from the development of wireless environmental sensors," *IEEE Trans. Instrum. Meas.*, vol. 69, no. 6, pp. 3470–3480, Jun. 2020, doi: 10.1109/TIM.2019.2938137.
[126] G. Mois, S. Folea, and T. Sanislav, "Analysis of three IoT-based wireless sensors for environmental monitoring," *IEEE Trans. Instrum. Meas.*, vol. 66, no. 8, pp. 2056–2064, Aug. 2017.
[127] M. Tacca, P. Monti, and A. Fumagalli, "Cooperative and reliable ARQ protocols for energy harvesting wireless sensor nodes," *IEEE Trans. Wireless Commun.*, vol. 6, no. 7, pp. 2519–2529, Jul. 2007, doi: 10.1109/TWC.2007.05878.
[128] S. Reddy and C. R. Murthy, "Profile-based load scheduling in wireless energy harvesting sensors for data rate maximization," in *Proc. IEEE Int. Conf. Commun.*, Cape Town, South Africa, May 2010, pp. 1–5, doi: 10.1109/ICC.2010.5502464.
[129] S. Reddy and C. R. Murthy, "Dual-stage power management algorithms for energy harvesting sensors," *IEEE Trans. Wireless Commun.*, vol. 11, no. 4, pp. 1434–1445, Apr. 2012, doi: 10.1109/TWC.2012.032812.110623.
[130] S. Escolar, A. Caruso, S. Chessa, X. D. Toro, F. J. Villanueva, and J. C. Lopez, "Statistical energy neutrality in IoT hybrid energy-harvesting networks," in *Proc. IEEE Symp. Comput. Commun. (ISCC)*, Natal, Brazil, Jun. 2018, pp. 00444–00449, doi: 10.1109/ISCC.2018.8538532.
[131] J. Yang, X. Wu, and J. Wu, "Optimal online sensing scheduling for energy harvesting sensors with infinite and finite batteries," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 5, pp. 1578–1589, May 2016, doi: 10.1109/JSAC.2016.2551561.
[132] O. H. Abdelrahman, "A Markov-modulated diffusion model for energy harvesting sensor nodes," *Probab. Eng. Informational Sci.*, vol. 31, no. 4, pp. 505–515, Oct. 2017, doi: 10.1017/s0269964817000158.
[133] M.-L. Ku, Y. Chen, and K. J. Ray Liu, "Data-driven stochastic models and policies for energy harvesting sensor communications," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 8, pp. 1505–1520, Aug. 2015, doi: 10.1109/JSAC.2015.2391651.
[134] R. Valentini, E. Bozorgzadeh, M. Levorato, N. Venkatasubramanian, and N. Dang, "A unified stochastic model for energy management in solar-powered embedded systems," in *Proc. IEEE/ACM Int. Conf. Comput.-Aided Design (ICCAD)*, Austin, TX, USA, Nov. 2015, pp. 621–626, doi: 10.1109/ICCAD.2015.7372627.
[135] C. Delgado, J. M. Sanz, C. Blondia, and J. Famaey, "Batteryless LoRaWAN communications using energy harvesting: Modeling and characterization," *IEEE Internet Things J.*, vol. 8, no. 4, pp. 2694–2711, Feb. 2021, doi: 10.1109/JIOT.2020.3019140.
[136] I. T. Castro, L. Landesa, and A. Serna, "Modeling the energy harvested by an RF energy harvesting system using gamma processes," *Math. Problems Eng.*, vol. 2019, pp. 1–12, Apr. 2019, doi: 10.1155/2019/8763580.
[137] D. Altinel and G. Karabulut Kurt, "Modeling of multiple energy sources for hybrid energy harvesting IoT systems," *IEEE Internet Things J.*, vol. 6, no. 6, pp. 10846–10854, Dec. 2019, doi: 10.1109/JIOT.2019.2942071.
[138] M. Chu, X. Liao, H. Li, and S. Cui, "Power control in energy harvesting multiple access system with reinforcement learning," *IEEE Internet Things J.*, vol. 6, no. 5, pp. 9175–9186, Oct. 2019, doi: 10.1109/JIOT.2019.2928837.
[139] D. Fan, L. L. Ruiz, J. Gong, and J. Lach, "EHDC: An energy harvesting modeling and profiling platform for body sensor networks," *IEEE J. Biomed. Health Inform.*, vol. 22, no. 1, pp. 33–39, Jan. 2018, doi: 10.1109/JBHI.2017.2733549.
[140] Semtech Corporation, Camarillo, CA, USA. (Dec. 2019). *LoRa and LoRaWAN: A Technical Overview*. Accessed: Dec. 20, 2020. [Online]. Available: https://lora-developers.semtech.com/library/tech-papers-and-guides/lora-and-lorawan/
[141] S. Kim and P. H. Chou, "Energy harvesting with supercapacitor-based energy storage," in *Smart Sensors and Systems*, Y. L. Lin, C. M. Kyung, H. Yasuura, and Y. Liu, Eds. Cham, Switzerland: Springer, 2015, doi: 10.1007/978-3-319-14711-6_10.
[142] B. Schweber. (Feb. 20, 2013). *Energy-Harvesting Storage Options: Rechargeable Battery, Supercapacitor, or Both?* Digi-Key Electronics, Thief River Falls, MN, USA. Accessed: Feb. 18, 2021. [Online]. Available: https://www.digikey.ro/ro/articles/energyharvesting-storage-options-rechargeable-battery-supercapacitor-or-both.
[143] A. S. Weddell, G. V. Merrett, T. J. Kazmierski, and B. M. Al-Hashimi, "Accurate supercapacitor modeling for energy harvesting wireless sensor nodes," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 58, no. 12, pp. 911–915, Dec. 2011, doi: 10.1109/TCSII.2011.2172712.
[144] R. G. Cid-Fuentes, A. Cabellos-Aparicio, and E. Alarcon, "Energy buffer dimensioning through energy-erlangs in spatio-temporal-correlated energy-harvesting-enabled wireless sensor networks," *IEEE J. Emerg. Sel. Topics Circuits Syst.*, vol. 4, no. 3, pp. 301–312, Sep. 2014, doi: 10.1109/JETCAS.2014.2337194.
[145] S. Zeadally, F. Siddiqui, and Z. Baig, "25 years of Bluetooth technology," *Future Internet*, vol. 11, no. 9, p. 194, Sep. 2019.
[146] K. E. Jeon, J. She, P. Soonsawad, and P. C. Ng, "BLE beacons for Internet of Things applications: Survey, challenges, and opportunities," *IEEE Internet Things J.*, vol. 5, no. 2, pp. 811–828, Apr. 2018, doi: 10.1109/JIOT.2017.2788449.
[147] Q. Liu, W. Ijntema, A. Drif, P. Pawelczak, M. Zuniga, and K. S. Yildirim, "Perpetual Bluetooth communications for the IoT," *IEEE Sensors J.*, vol. 21, no. 1, pp. 829–837, Jan. 2021, doi: 10.1109/JSEN.2020.3012814.
[148] H. Yao, H. Shu, X. Liang, H. Yan, and H. Sun, "Integrity monitoring for Bluetooth low energy beacons RSSI based indoor positioning," *IEEE Access*, vol. 8, pp. 215173–215191, 2020, doi: 10.1109/ACCESS.2020.3038894.
[149] P. Spachos and K. N. Plataniotis, "BLE beacons for indoor positioning at an interactive IoT-based smart museum," *IEEE Syst. J.*, vol. 14, no. 3, pp. 3483–3493, Sep. 2020, doi: 10.1109/JSYST.2020.2969088.

[150] P. Octaviani and W. Ce, "Inventory placement mapping using Bluetooth low energy beacon technology for warehouses," in *Proc. Int. Conf. Inf. Manage. Technol. (ICIMTech)*, Bandung, Indonesia, Aug. 2020, pp. 354–359, doi: 10.1109/ICIMTech50083.2020.9211206.
[151] *AMS AG. CCS811 Gas Sensor Solution Ultra-Low Power Digital Gas Sensor for Monitoring Indoor Air Quality*, AMS AG: Premstaetten, Austria, 2018.
[152] *Cypress Semicond. Corporation, CYBLE-022001-00 EZBLE PRoCModule-Cypress*, Cypress Semicond. Corp., San Jose, CA, USA, Feb. 2016.
[153] *SENSIRION AG, Datasheet SHT21-Humidity and Temperature Sensor IC, Version, 4th ed.*, Sensirion, Staefa, Switzerland, May 2014. [Online]. Available: https://www.sensirion.com
[154] *NXP Semiconductors, Miniature I2C Digital Barometer, Review*, NXP Semicond., Eindhoven, The Netherlands, Feb. 2013.
[155] *OPT3001 Ambient Light Sensor (ALS)*, Texas Instrum., Dallas, TX, USA, Jul. 2014.
[156] *BQ25504 Ultra Low-Power Boost Converter With Battery Management for Energy HArvester Applications*, Texas Instrum., Dallas, TX, USA, Oct. 2011.
[157] IXYS UK Westcode Ltd, Chippenham, U.K. (Nov. 2013). *Product Brief-IXYS Solar Products, 3rd ed.* [Online]. Available: http://ixapps.ixys.com/DataSheet/ixys_solar.pdf
[158] MULTICOMP. (Oct. 13, 2020). *Lithium-Ion Rechargeable Battery (Coin Cell, Lithium, 3V, 120mAh-LIR2450)*. Accessed: Feb. 6, 2021. [Online]. Available: https://ro.farnell.com/b/multicomp
[159] Texas Instruments, Dallas, TX, USA. (Nov. 2014). *TPS783xx 500-nA IQ, 150-mA, Ultralow Quiescent Current Low-Dropout Linear Regulator*. Accessed: Feb. 6, 2021. [Online]. Available: http://www.ti.com/lit/ds/symlink/tps783.pdf
[160] *P1110-EVB—Evaluation Board for P1110 Powerharvester Receiver Technical Manual*, Powercast Corp., Pittsburgh, PA, USA, 2015.
[161] (Sep. 17, 2020) *BU-808: How to Prolong Lithium-Based Batteries*. Accessed: Dec. 17, 2020. [Online]. Available: https://batteryuniversity.com/learn/article/how_to_prolong_lithium_based_batteries
[162] J. Estrada-López, A. Abuellil, Z. Zeng, and E. Sánchez-Sinencio, "Multiple input energy harvesting systems for autonomous IoT end-nodes," *J. Low Power Electron. Appl.*, vol. 8, no. 1, p. 6, Mar. 2018, doi: 10.3390/jlpea8010006.

TEODORA SANISLAV (Member, IEEE) received the B.S. degree in computer science and the Ph.D. degree in systems engineering from the Technical University of Cluj-Napoca, Romania, in 2003 and 2013, respectively.

From 2004 to 2011, she was a Scientific Researcher in automation with the research institute. She is currently a Lecturer with the Automation Department, Technical University of Cluj-Napoca. Her current research interests include cyber-physical systems, dependability analysis, the Internet of Things, and intelligent systems.

GEORGE DAN MOIS (Member, IEEE) received the Ph.D. degree in systems engineering from the Technical University of Cluj-Napoca, Cluj-Napoca, Romania, in 2011.

Since 2017, he has been a part of the Innovation and Universities Group, Bosch Engineering Center Cluj. He is currently a Lecturer with the Automation Department, Technical University of Cluj-Napoca. His current research interests include embedded system design and wireless sensor networks.

SHERALI ZEADALLY (Senior Member, IEEE) earned his bachelor's degree in computer science from the University of Cambridge, England. He also received a doctoral degree in computer science from the University of Buckingham, England, followed by postdoctoral research at the University of Southern California, Los Angeles, CA. He is currently an Associate Professor in the College of Communication and Information, University of Kentucky. His research interests include cybersecurity, privacy, Internet of Things, computer networks, and energy-efficient networking. He has received numerous awards and honors for his research and teaching. He is a Fellow of the British Computer Society and the Institution of Engineering Technology, England.

SILVIU CORNELIU FOLEA (Senior Member, IEEE) received the Ph.D. degree in control systems and the Habilitation degree from the Technical University of Cluj-Napoca, Cluj-Napoca, Romania, in 2005 and 2017, respectively.

He is currently a Professor with the Department of Automation, Technical University of Cluj-Napoca. His current research interests include the development of wireless environmental sensors, energy harvesting, embedded and reconfigurable systems, data acquisition systems, and graphical programming.