Recent Advances In Energy Management For Green-IoT: An Up-To-Date And Comprehensive Survey

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Abstract

Internet-of-Things (IoT) refers to the massive network interconnection of objects often equipped with ubiquitous intelligence employed to provide smart services to end users. However, one of the substantial issues of IoT is the limited energy of IoT devices that are expected to run consistently for a long period of time without battery replacement. Moreover, in the wake of pervasive IoT, the number of IoT devices has exploded and lead to a tremendous rise in IoT networks carbon footprint. In this regard, Green-IoT and energy management of IoT emerged as challenging and attractive research topics for both academia and industry. In this paper, we conduct a comprehensive and an up-to-date survey on recent energy management techniques in IoT networks. We start by presenting the challenges of energy consumption in IoT networks. Then, we will present novel and well-known energy management approaches for IoT but focus on the most recent solutions proposed in each approach. Next, we will provide a comprehensive survey of the most recent energy management solutions for IoT ecosystem. We will also present recent trends and new research perspectives that can be exploited for energy conservation in IoT networks. Finally, we will give recommendations on how to exploit the techniques presented in our survey to achieve the IoT applications QoS requirements.

Keywords: Internet-of-Things (IoT), Green-IoT, Energy Management, Energy Harvesting, Energy Saving.

1. Introduction

The Internet of Things (IoT) is a paradigm that envisions to connect everyday objects and integrate them to the internet using microcontrollers, transceivers, and protocol stacks. This paradigm attracts the attention of both academia and industries and aims at the digitization of a plethora of applications with high societal relevance. The IoT applications in our daily life activities are manifold, from smart transportation that offers ground breaking progress in the transportation and logistic industry to smart home that facilitates its in-habitants activities. IoT covers several fields such as smart traffic, healthcare, agriculture, industry 4.0 and can even be found in our everyday objects such as pens, clothes, etc. As a result, the world has known an explosive growth in the number of these devices. According to IHS Markit, 125 billions of IoT devices are expected to be connected with each other by 2030 [1]. This number is highly influenced by the emergence of 5G networks and the exploitation of new spectrum frequencies [2]. Moreover, IoT devices are usually small and battery limited and the exchange of massive information between these devices gives rise to enormous energy requirements. These requirements are often not supported by IoT devices and can quickly lead to battery depletion and the network's death. So, how can we develop energy-efficient solutions that will not only reduce the energy consumption in IoT networks and their carbon footprints but also increase the networks lifetime? Accordingly, we witness the emergence of the Green Internet of Things which focuses on saving and managing energy in IoT networks in order to optimize and reduce the energy consumption and prolong the IoT networks lifetime. In the next few years, Green IoT will make significant changes in our daily life and will help realize

Table 1: The Table Shows a Comparison of the Main Features of This Survey With Those found in Literature

	[3]	[4]	[5]	[6]	This survey
Green IoT enabling technologies	No	Yes	Yes	No	Yes
Energy harvesting	Yes	No	No	Yes	Yes
Energy saving	Yes	Yes	Yes	Yes	Yes
Taxonomy of the energy management solutions	Yes	Yes	No	Yes	Yes
Intelligent energy management solutions	No	No	No	No	Yes
IoT Network Softwarization energy saving solutions	No	No	No	No	Yes
5G IoT energy saving solutions	No	No	No	No	Yes
Social IoT energy management solutions	No	No	No	No	Yes
Backscatter Communication technology	No	No	No	No	Yes
Wake-up Radio technology	No	No	No	No	Yes

the vision of ”green ambient intelligence” [7]. In this survey, we are going to present a wide range of energy harvesting and energy saving techniques and set out the recent research trends for Green IoT such as green 5G IoT, green social IoT, green networks softwarization, backscatter communications, etc.
This paper is organized as follows : In Section 2, we present the background information on the energy management works presented in the literature. In Section 3, we describe the problem and challenges of energy consumption in IoT networks. In Section 4, we discuss and select some of the energy harvesting and energy saving techniques presented in the literature focusing on the most recent researches. In Section 5, we present the energy management technologies for IoT ecosystem. In Section 6, we discuss the recent trends and research perspectives that can be exploited in energy management for IoT. Finally, we shall conclude the paper by providing an insight into open research problems and the future of Green IoT.

2. Background

The subject of energy management for IoT networks has been widely studied and various reviews and surveys were presented throughout the years. Researchers are interested in energy efficient WSNs since they are widely deployed and omnipresent in IoT. In [3], the authors presented battery-driven energy conservation and energy harvesting schemes used to design algorithms in Wireless Sensor Networks (WSNs). The authors focused on reviewing the protocols used for the energy management of wireless sensor networks. Compared to this survey, our survey does not only focus on sensors but the different devices IoT networks can include. In [6], the authors surveyed energy saving and energy management schemes and energy efficient protocols for WSNs focusing on transmission power management and miscellaneous techniques. Compared to our survey, this survey does not include the energy harvesting and wireless charging solutions of IoT networks. In [8], the authors surveyed the energy harvesting approaches used in WSNs which help to improve WSN lifetime. Compared to our survey, this survey focus only on energy harvesting of wireless sensor networks and not the different types of devices we can have in IoT networks. In our work, we present solutions not only energy saving and harvesting solutions for sensors but also rich resources devices.

In the recent years, more and more authors started to use the

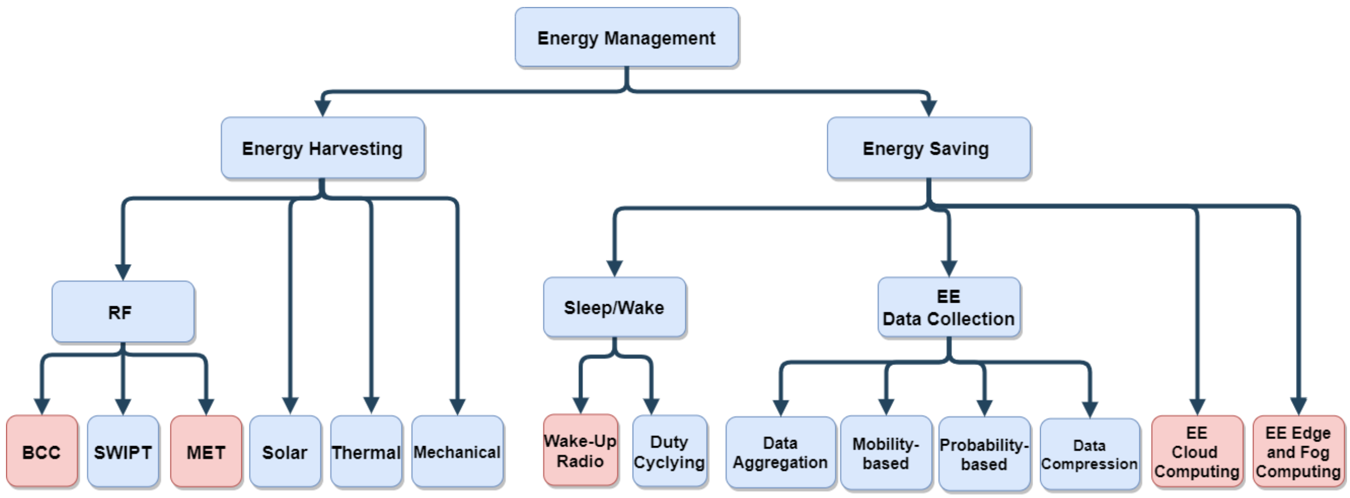

Figure 1: Taxonomy of Energy Management Techniques

Green IoT appellation. Green IoT refers to the energy efficient hardware or software procedures used to reduce the greenhouse effect of existing IoT applications and services as well as the impact of greenhouse effect of IoT itself [5]. It represents all the enabling technologies for Green IoT such as Green RFIDs (radio frequency identification), Green Datacenters, Green Sensor Networks, Green Cloud Computing, Green Edge Computing and Green Communications. In [9], a Green IoT life cycle is presented which includes: green design, green production, green utilization, green recycling in addition to green IoT technologies such as green tags, green sensing networks and green Internet technologies. In [4], the authors discussed IoT techniques to achieve Green IoT and proposed a taxonomy of energy efficient based on the technologies used in IoT while in [10], the authors discussed energy efficiency techniques of different components and layers of IoT networks. Compared to our survey, the previous works do not include the energy harvesting techniques for IoT networks. In Table 1, we present a comparison between our survey and the other energy management and Green IoT surveys. It is clear through Table I that, in our survey, we chose to present novel schemes that were not discussed in the surveys presented previously. The main purpose of our paper is to provide an up-to-date state-of-art about energy management and Green IoT. Our comprehensive survey discusses the different and most recent techniques used in order to reduce energy consumption and increase the networks lifetime in IoT networks. Therefore, this article aims to serve as a guideline for researchers interested in the trends of energy management IoT networks.

3. Problem statement and challenges

Since IoT applications and services are reaching almost every corner our life, the carbon footprint of these applications is increasing proportionately with the number of IoT devices. IoT networks are composed of devices that can be rich or limited in energy resources. The aim of Green IoT is to reduce the energy consumption of both types of devices while still being able to effectively perform their tasks and services. Key and widespread IoT technologies such as wireless sensor networks are composed of small and battery limited sensor devices that gather information and build efficient and reliable information and communication systems. However, these devices are typically used to perform monitoring and control tasks in IoT applications over long periods of time and without interruption. Sensors can also be placed in areas which are difficult to access (e.g. under water systems, military systems, unsafe environments, etc.) and can quickly run out of energy. Consequently, replacing their batteries frequently becomes an arduous and costly task. Energy storage and power management should also ensure the constant availability and operability of IoT de-

Table 2: The Table Shows The State-Of-The-Art of Energy Harvesting In The literature

Energy Harvesting Technologies		**References**
RF Source energy harvesting	**Backscatter Communications**	[11], [12], [13], [14], [15], [16], [17], [18]
	SWIPT	[19], [20], [21], [22], [23],[24], [25], [26], [27]
	MET	[28],[29], [30], [31]
Solar Energy Harvesting		[32], [33], [34], [35], [36]
Thermal Energy Harvesting		[37], [38], [39], [40]
Mechanical Energy Harvesting		[41], [42], [43]

vices given that, neither cable-power nor battery replacement are feasible options in harsh conditions. Many energy saving software and hardware solutions, which we will present in our survey, have been developed in order to reduce IoT networks energy consumption and maintenance cost.

Currently, the world experiences a scarcity in energy sources in addition to the important emission of CO2 resulting of human activity. Greening information and communication technologies becomes an imperious need considering the damages caused on our environment. Consequently, energy harvesting solutions has been studied in order to power IoT devices with green and renewable energies such as solar energy, wind energy, mechanical energy, etc.

Since Green IoT is a newly studied research field, one essential domain that is not widely discussed is energy measurement. In fact, with the battery limited nature of IoT devices and their high number and energy consumption, measuring and analyzing the energy consumption of IoT devices is key to achieve applications' QoS requirements. Due to the high cost and large size of the existing commercial energy measurement solutions, researchers proposed various alternatives. However, these alternatives are often limited with their complexity, measurement range and accuracy [44]. IoT energy measurement tools should also be standardized to be able to support all types of devices with their different complexities at a low cost.

As we can see, although the revolution of IoT changing our lives has started, many challenges still need to be overcome in terms of energy consumption and environmental issues. Accordingly, numerous potential solutions in different disciplines are being explored to achieve this goal that requires a lot of efforts.

4. Energy management Techniques

In order to tackle the energy issues in IoT networks, two approaches are usually employed: energy harvesting and energy saving. Energy harvesting can be described as the mechanisms employed to produce energy from a network ambient environment to provide an uninterrupted power supply for the network devices. On the other hand, energy saving schemes focus on developing algorithms, protocols and even hardware solutions to minimize the network energy consumption and maximize its lifetime. Based on these two categories, we propose a technique-based taxonomy (Fig. 1) which represents the recent energy management solutions studied in the literature in order to extend IoT networks lifetime and reduce the carbon footprint of those networks. Our taxonomy includes recent energy management techniques that can be found in the literature and not discussed in previous surveys.

As shown in Fig. 1, we divide the energy harvesting category in the taxonomy depending on the energy sources into four sections: RF energy harvesting in which we include Backscatter

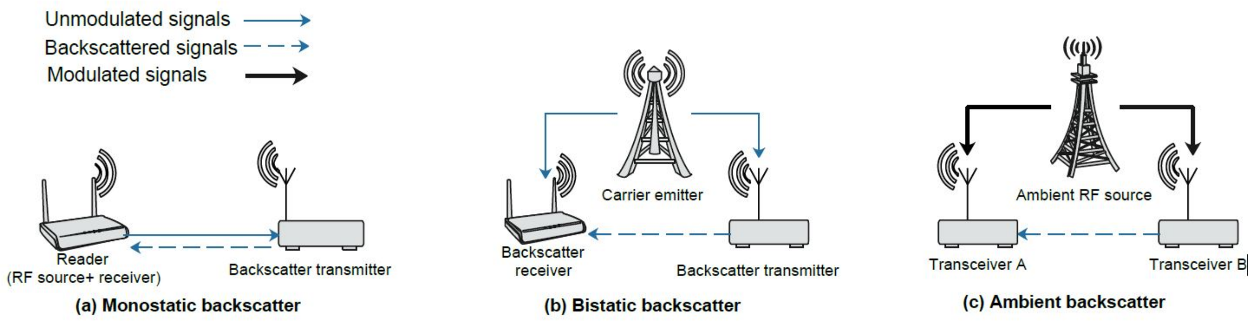

Figure 2: Backscatter Communication paradigms

Communications (BCC) [11], a novel energy harvesting technology that have not been mentioned in previous energy management and Green IoT surveys, Mobile Energy Transfer (MET) and Simultaneous Wireless Information and Power Transfer (SWIPT) technology. We also discuss the most recent researches in energy harvesting techniques with green sources such as : solar, thermal and mechanical energy. We will present these techniques more deeply later in this section. The second category of energy management solutions we represent in the taxonomy includes energy saving solutions. As shown in Fig. 1, we classified energy saving solutions depending on the technology they employ. Unlike existing energy management surveys, in our survey, we introduce recent intelligent energy saving techniques that use Machine Learning (ML) and Deep Learning (DL) to reduce the energy consumption in IoT networks. We present energy efficient data collection techniques used in IoT networks as well as, sleep/wake-up schemes such as Duty Cycling and the recent low power Wake-Up Radio technology which have not been presented in the existing energy management and Green IoT surveys.

In what follows, we will discuss the energy management techniques for IoT networks. First, we start by presenting the energy harvesting techniques followed by the energy saving techniques discussed in the literature. It is worth mentioning that we will present and focus more deeply on the emerging energy management techniques which have not been discussed in previous surveys.

4.1. Energy Harvesting Techniques

We will discuss the energy harvesting techniques existing in the literature. We focus our review on the recent solutions proposed for each one of these techniques. In Table 3, we present the concept and challenges of the energy harvesting techniques presented in our survey and Table 2 summarizes the energy harvesting works organized by the nature of the harvested energy: *RF, solar, thermal and mechanical energy.*

4.1.1. RF energy harvesting (Wireless Power Transfer Techniques)

In what follows, we will present RF energy harvesting techniques focusing deeply on backscatter technology since it is an emerging technique in energy harvesting that has not been presented in previous surveys.

1. *Backscatter Communications*

   One of the major issues that IoT networks face is the limited network lifetime due to the battery dependency of IoT devices. Having these devices completing task over a long period of time could easily lead to battery depletion and induce a replacement cost. In some cases, sensors do not need to be kept active consistently and will wear out their batteries unnecessarily. Backscatter communications allows battery-less devices to transform wireless signals and use them as a source of power and a communication medium. Having battery-less devices is a major advantage of backscatter communications as it helps reducing energy consumption, removes the constraint of

Table 3: The Table Shows The Energy Harvesting Techniques and their challenges

Energy Harvesting Techniques	Concept	Challenges
Backscatter communication	-Batteryless devices -Use RF signal to code information and send it to the receiver	-Short range -Efficient information coding -Security -High deployment cost
SWIPT	-Battery less or battery powered devices -The information and power for the device are sent through the same signal	-Efficient information decoding -Interference -Short range -Security
MET	-Use a mobile node to power IoT devices	-The energy consumption of the mobile node -Interference
Solar Energy Harvsting	-Use solar energy to power devices	-Light availability -Energy transport
Thermal Energy Harvesting	-Generate electric power from the difference in temperature	-Efficient power generation
Wind/Water Energy	-Generate electric power from water and wind movement	-Difficult to deploy -Unpredictable
Humain Motion	-Generate electric power from human movement	-Low energy -Differs from one person to another

frequent battery replacement and averts from undesired performances due to energy shortage.

According to [11], there are three different paradigms of Backscatter Communications (Fig. 2): *Monostatic Backscatter Communication (MBC), Bistatic Backscatter Communication (BBC) and Ambient Backscatter Communication (ABC).*

- *Monostatic Backscatter Communication:* as shown in Fig. 2(a) MBC system is composed of two components: a reader and a backscatter transmitter (e.g. a RFID tag). The specificity of MBC is that the receiver and the RF source are located in the reader. The RF source sends a signal that activates the tag which modulates the signal and reflects it back to the backscatter receiver. Since the RF source and the receiver are located in the same device, the modulated signals may suffer from a round trip path loss which makes it more suited for short-range RFID application.

- *Bistatic Backscatter Communication:* the main difference between BBC and MBC systems lies in the separation of the RF source (renamed the carrier emitter in BBC) and the backscatter receiver in different components which significantly reduce the round-trip path-loss problem (as represented in Fig. 2(b)). Moreover, by optimaly placing carrier emitters, the overall communication range can be extended and the system performance is greatly improved. Although the deployment and maintenance of the carrier emitters in BBCs are costly, their design remains simple which makes their manifacturing cost lower than MBCs.

- *Ambient Backscatter Communication:* in Ambient backscatter communication systems (Fig. 2(c)) and similarly to BBC systems, ABC systems carrier emitter is separated from the backscatter receiver. However, the carrier emitter, in this case, can be an already available ambient RF source in the environment such as a Wi-Fi access point or a cellular base station. In [12], an ABS system is presented as a batteryless device (tag or sensor) which can harvest wireless energy from a RF source and then transmit "0" or "1" bit to a sink node through reflecting or non-reflecting states. In addition to having virtually no cost of deployment, the manufacturing costs and power consumption of ABCs can be reduced by the use of low-cost and low-power components.

Various works studied the backscatter communications and its impact on the energy consumption of IoT networks and proposed solutions to further improve the energy efficiency of these systems. In [13], the authors proposed a cooperative ambient backscatter communication system which allows a device to recover information from both the ambient backscatter devices and the RF source. The proposed solution enhances the maximum-likelihood detection performance if the backscatter device symbol period is longer than the RF source symbol period. This solution can be upgraded to be exploited in smart home and wearable applications. In order to further enhance the energy efficiency of backscatter communications, various works studied the optimization of the communication parameters. The authors in [14] proposed a joint optimization based on the source antenna number and power splitting factor under the condition that the minimum energy required by the destination node is met while in [15], the authors proposed a solution to optimize the needed power to transmit for a base station and the radio of backscattered signal of the IoT devices in the context of massive IoT. For complex IoT systems, other parameters (such as the number of base stations, the number of backscatter devices and their positions) need to be optimized in order to be energy efficient and to adapt to the IoT application needs. The authors in [16], focused on the link layer of backscatter communication systems using centralized MAC protocols, while other solutions used distributed MAC protocol [17],[18]. Distributed MAC protocols are more suitable than the centralized protocols for large-scale IoT networks with unstable network topologies and high topology maintenance cost.

Although backscatter communications seem ideal to achieve green IoT, it still has to overcome some challenges such as the risk of interference when there is a high number of nodes as well as, the bit rate limitations as it is not simple to implement very complex modulations on a backscatter tag due to its limited capability in manipulating the RF signal and performing baseband processing. In addition to that, backscatter communications networks need to overcome the short range limitation and the high deployment cost they may generate.

2. *Simultaneous Wireless Information and Power Transfer (SWIPT)*
SWIPT is one of the most attractive and challenging technologies in energy management. It is a technique that enables the simultaneous transfer of information and power wirelessly [19]. Theoretically, SWIPT allows an IoT device to harvest energy and receive RF information from the same RF signal that carries both energy and information. Therefore, an IoT device can be self-powered by receiving data. However, in most of the cases, it is not possible to perform energy harvesting and information decoding simultaneously from the same signal. The information could be altered or lost by the energy harvesting operation. Thus, different receiver architectures were designed to achieve SWIPT: *Separate Receiver, Time Switching (TS), Power Splitting(PS) and Antenna Switching* [19]. In SWIPT, the power and information needed for an IoT node are sent at the same time which keeps the node alive and extend the lifetime of IoT networks. Various solutions have been proposed to adapt and achieve SWIPT. For example, in [20], the authors provide a comprehensive study related to SWIPT in different types of wireless communication setups. In [21], the authors proposed a dual-battery green energy harvesting architecture that achieves SWIPT. It consists in using one battery to power the device while the other one is harvesting energy in order to reduce energy shortage probability. However, this solution is limited to small IoT networks with devices that can support a dual battery. The proposed solution also adds complexity to sensor devices and is expensive for massive IoT networks with a high number of devices. In [22], the authors proposed a collaborative energy and information transfer protocol for WSN that does not require the power and information splitter component which is convenient for IoT networks and reduces the sensors complexity and cost. In [45], the authors studied the optimization of the energy efficiency in a SWIPT-based distributed antenna system by coordinating the energy harvesting and information decoding for IoT devices. The proposed solutions take into consideration the number of IoT devices in the network.

SWIPT was also associated with deep learning to further enhance the energy saving potential of this technology. In [24], the authors proposed a solution based on deep learning to minimize the total transmit power of a multi-carrier NOMA SWIPT system while satisfying the Quality-of-Service (QoS) requirements of each user. Deep learning was also used with SWIPT in [25]. The authors proposed a dual mode SWIPT system that uses an adaptive mode switching based on deep learning to exploit both single tone and multi-tone SWIPT. Although deep learning proves to be efficient for SWIPT-based system, it also requires an important amount of resources that should be considered to build green and sustainable IoT networks. In [26], the authors proposed a hybrid resource and task

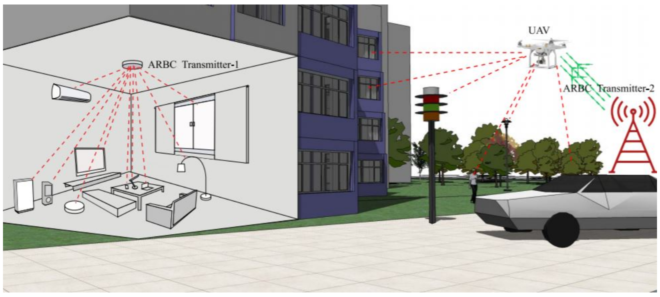

Figure 3: Mobile Energy Transfer RBC scenario

algorithm in a SWIPT system that enables the devices to do their requirement tasks in a distributed manner. However, this solution should be improved to take into consideration delay-sensitive tasks for it to satisfy the real-time requirement of IoT applications. Finally in [27], the authors proposed a cooperative SWIPT scheme that consists of a conflict-free schedule initialization algorithm, a cooperative resource allocation algorithm and a heuristic algorithm to obtain a maximum energy efficiency in the transmission schedule with the appropriate resource allocation policy.

SWIPT is theoretically a very efficient energy harvesting technique. However, this technique offers several challenges. In SWIPT, the information and energy are sent through the same signal. This signal needs to be efficiently decoded in order to recover the correct information. The signal can also be altered by the energy harvesting mechanisms or by interference. SWIPT is limited in range since the signals can weaken when crossing long distances. Finally, signals that are sent to the devices can be hijacked by hackers. Therefore, a level of security should be added in order to protect potential private and personal data.

3. *Mobile Energy Transfer*

Mobile energy transfer is an ambitious energy efficient technique for IoT networks. It extends wireless power transfer technologies since the use of classical wireless power transfer technologies is not suitable if the node is isolated, placed in areas which are difficult to access and does not support free charging. Mobile energy transfer consists in giving to a mobile node (such as a car, a bus, etc), the ability to transfer energy to the devices within its transmission range.

Various works have studied the use of mobile energy transfer technology for IoT networks energy management. The energy consumption of the mobile node is a key challenge of mobile energy transfer enabled IoT networks. In [28], the authors proposed a solution to minimize the total energy consumption of a mobile base station while supporting the data and energy demands of IoT devices to guarantee the QoS. This study shows that various parameters can impact the energy consumption of MET based IoT networks such as the mobile base station locations and its movement speed, the number of devices and their tolerable time for delivering data and energy as well as the transmission powers (the power needed for energy and data transmission). In [29], the authors proposed a hierarchical and wireless energy transfer using mobile chargers in Wireless Rechargeable Sensor Networks while in [30], the authors presented one of the mobile energy transfer technologies called Adaptive Resonant Beam Charging (ARBC). As shown in Fig. 3, it consists of two specially separated components: a transmitter and a receiver (car, TV, etc.) and in some cases, a relay (UAV in Fig. 3) which is used to relay the energy between the transmitter and the receiver. In [31], the authors proposed a mobile power network based on long range and short range wireless power transfer technologies and discussed the challenges of MET such as interference, efficiency, range and topology.

4.1.2. *Solar energy harvesting*

Given its abundance in the environment, solar energy is considered as an affordable and clean energy source that could eliminate the energy shortage problem in IoT networks. This technique directly converts sunlight into usable electricity which is convenient for location with high light availability. However, the solar energy harvesting technique flaws arise in locations where light availability cannot always be guaranteed. Additionally, transporting solar energy from a location to another when needed may cause considerable energy waste which shows that there is still room for research and improvement in this area.

In the literature, various authors studied solar energy harvesting for IoT networks. In [32], the authors presented a review on solar energy harvesting for IoT applications and discussed the use of artificial intelligence and more specifically artificial neural networks to enhance and rapidly design energy harvesting systems for IoT applications. Numerous authors proposed solutions on solar energy harvesting for WSNs in [33], [46] and [34]. In [33], the authors proposed an intelligent solar energy harvesting system based on maximum power point tracking for wireless sensor nodes used in IoT, which prefers to use the solar power and takes the lithium battery as a supplementary under the condition of inadequate illumination. This solution offers IoT systems more reliability in case of scarcity in solar energy in the area. In [46], the authors proposed an energy prediction algorithm that uses the light intensity of fluorescent lamps in an indoor environment for wireless sensor nodes for IoT. This solution can be particularly helpful to achieve green and sustainable smart home since lamps can be used to power the sensors used in the smart home. In [34], the authors proposed a new routing algorithm that aims to improve the lifetime of sensor nodes as well as the QoS under variable traffic load and solar and RF energy availability. The proposed algorithm significantly improves the energy efficiency of the IoT network even if the number of nodes increases drastically which constitutes a suitable solution for massive, complex and scalable IoT networks. In [35] and [36], the authors proposed a solution to improve solar energy harvesting in wearable IoT applications. In [35], the authors proposed an MPPT algorithm based on the output current to extract the maximum power from a flexible solar panel to power wearable pulse sensors. Finally, in [36], the authors presented a self-powered wearable IoT sensor network that uses solar energy and is designed for safety environmental monitoring.

4.1.3. Thermal Energy Harvesting

Thermal energy is the energy that comes from heat and variation in temperature. The human body and the environment can be a source of thermal energy. For example, a difference in temperature can be created by the human body and the environment depending on the health condition, the location of a person, or body motion. There are two techniques that are used in thermal energy harvesting: thermometric, a technique that directly converts temperature difference into usable energy and pyroelectric, a technique that generates electrical energy when there is a change in temperature. It is important to efficiently generate electric energy from thermal generator in order to extract maximum electric energy to power devices and exploit the maximum potential of this approach.

In the literature, various authors tackled the subject of thermal energy harvesting for IoT. In [37], the authors discussed the use of thermal energy harvesting approach to power up a wireless sensor node for IoT applications. This study shows the efficiency of using thermal energy to power IoT nodes and the importance of using thermal energy harvesting in long-term IoT applications. Thermal energy harvesting proves to be efficient for various IoT applications. For example, in [38], the authors studied the use of energy thermal harvesting for self-powered smart home sensors. For healthcare, in [39], the authors studied a human body heat-based solution for wearable biomedical IoT nodes. Finally, in [40], the authors proposed a solution to optimize the energy consumption of thermal energy in IoT nodes by proposing an intelligent control of the individual parts of an IoT node. Unlike in [37], This solution uses a battery to store the harvested energy and then uses the nodes' battery to power the application.

Table 4: The Table Shows The Utility Of Energy Harvesting Techniques In Major IoT Applications

Energy Harvesting Technologies		Smart Building	Healthcare	Agriculture	Industrial IoT
RF Source Energy Harvesting	**Backscatter Communications**	+++	+	+++	+
	SWIPT	+++	+++	+++	+++
	MET	+++	+++	+++	+++
Solar Energy Harvesting		+++	+++	+++	+
Thermal Energy Harvesting		+++	+++	+++	+++
Mechanical Energy Harvesting	**Human motion**	+	+++	+	+
	Wind/Water Flow	+++	+++	+++	+++

4.1.4. Mechanical Energy Harvesting

Mechanical energy harvesting consists in harvesting the energy that results from movement, pressure, human activity or any type of motion from an object. It is considered as a very efficient energy harvesting solution since the more and faster the object moves the more energy is produced to do more tasks. Mechanical energy comes from various sources such as wind and water flow or human motion and can be converted into electrical energy and exploited to supply IoT devices. For example, it can be interesting to use the energy produced from human motion to power a human temperature monitoring device that the user wears or powering neighbouring houses using energy produced by wind and water flow. Mechanical energy harvesting offers a wide range of possibilities which makes it an ideal solution for creating green and sustainable applications.

In the literature, mechanical energy harvesting have been thoroughly discussed. Several authors focused on wind flow and hydro in [41] and [42] respectively. In [41], the authors discussed the use of wind energy in autonomous WSNs and weather forecast to improve the prediction of wind condition in the near future. In this solution, the authors used a one and two hours weather forecast window in case of zero wind energy which shows that the unpredictable nature of wind energy makes it unsuitable for IoT applications that require constant availability and real-time performances. In [43], the authors studied kinetic energy harvesting for wearables resulting from human motion. This study shows that human motion can produce an impressive amount of energy per day however, since the energy produced can vary from one person to another it can be difficult to develop a solution that is destined to a large population. In [42], the authors described the conception, modelling, calculation, design, manufacturing and validation of the performances of energy harvesting devices deployed in river streams to be employed as a power source for pollution monitoring wireless sensor clusters.

4.1.5. Discussion

The energy harvesting techniques presented in the previous sections are employed to produce energy from their surrounding environment and to power IoT networks. In Table 3, we summarize the energy harvesting techniques presented previously and the ability to use them in, what we consider, the major IoT applications (smart home, healthcare, agriculture and industrial IoT). For RF source harvested energy, SWIPT and MET can be applied to the use cases listed previously. In case of backscatter communications, the technology is suitable for smart homes, agriculture applications and indoor medical appli-

Table 5: The Table Shows The State-Of-The-Art of Energy Saving In The literature

Energy Saving Technologies		**References**
Sleep Scheduling	**Wake-Up Radio**	[47], [48], [49], [50], [51],[52], [53],[54]
	Duty Cycling	[55], [56],[57]
Energy Efficient Data Collection	**Data Aggregation**	[58], [58],[59], [60], [61]
	Probability Approach	[62]
	Compressive Sensing Approach	[63], [64], [65], [66]
	Mobility based approaches	[67], [68], [69], [70],[71]

cations. Backscatter communications is still at a development stage, therefore, it faces limited-range, security and interference problems which makes it not suitable for applications that handle critical data and require a high level of reliability such as industrial and outdoor medical applications. Solar energy harvesting is largely used in smart homes and buildings, healthcare and agriculture. However, while solar energy can be used in industrial IoT, the network designers should take into consideration the uncontrollable nature of solar energy and how it can affect the performance of the high reliability requirements of industrial IoT applications.

As shown in Table 4, thermal energy can be employed in different IoT applications as it can be frequently produced and stored to supply IoT devices. In case of mechanic energy harvesting, human motion is considered suitable for healthcare application. However, it does not produce enough energy to be helpful in the other applications. Wind and water flow can produce enough energy for various application, however, the uncontrollable nature of those energies is unsuitable for industrial IoT applications which require high availability and no energy shortage.

4.2. Energy Saving techniques

In this section, we discuss the existing energy saving techniques in the literature by presenting and focusing on the most recent solutions proposed in each one of these techniques. In Table 5, we summarize the energy saving works studied in our survey.

4.2.1. Sleep/Wake-Up Techniques

1. *Wake-Up Radios:* Wake-Up Radio is a novel hardware solution that has been developed to reduce the energy consumption of devices and extend the network lifetime. It consists in having a low power radio attached to the device main radio in charge of waking it up when an incoming signal is sensed. In IoT systems, a Wake-up Radio enabled IoT device has been defined in [47]. It is a microcontroller unit associated with a main radio and a wake-up receiver. The microcontroller and the main radio are in deep sleep most of the time. As shown in Fig. 4, when the receiver receives a request by means of a wake-up signal transmitted by an external node, it generates an interrupt signal to wake up the microcontroller to perform certain tasks and transmit data back via its main radio.

   Based on power usage, three types of wake-up radios have been identified [48]: active, passive and semi-active wake-up radios. Active wake-up radios require continuous external power supply such as batteries. Passive wake-up radios do not need energy from power supplies. They harvest energy from the transmitted signal instead. In semi-active wake-up radios, some components of the receiver require continuous power from an external source while the RF front-end remains passive. Wake-up radios can be particularly useful in a smart home/office scenario, or in an industrial context like warehouses and can be enhanced further to be used in smart cities [49]. However, due to the sleep and wake-up nature of wake-up radio, we can expect an increase in data reception latency.

According to [48], designing wake-up radio in a larger environment requires considering different design aspects such as:

- *Power consumption:* the node's power consumption should not exceed the main radio's sleep power to keep the balance between the energy saved and used by the device.
- *Time to wake-up:* the time needed to wake-up the device radio should be minimum in order to reduce the latency and thus enlarge the spectrum of applications Wake-up Radios can be used for.
- *False wake-ups and interference:* due to interference and wrongly receiving signals intended to other devices, a node or several nodes could be unnecessarly activated causing huge energy waste. Thus, designers should find the right compromise and find solutions to those challenges without increasing the energy consumption.
- *Sensitivity:* in Wake-up Radio environment, the sensitivity of the receiving node has a considerable impact on the power demand as having high sensitivity requires high power demand at the receiving side and having low sensitivity means needing high radiated power at the transmitter side.
- *Communication range:* the range of a Wake-up Radio has an impact on the type of application it is used in, as well as on the system's power consumption. For example, having short range communication would require a multi-hop communication which will increase the nodes density and the power consumption.
- *Data rate:* having a higher data rate in a Wake-up Radio context is a way to improve energy efficiency and wake-up latency. Similarly, having a longer bit duration also increases the communication range and the reliability of the wake-up signal.
- *Cost and size:* the Wake-up Radio should be cost effective in order to be integrated into the IoT context and existing sensor nodes. The cost should not exceed 5-10 per cent of the complete sensor node cost.
- *Frequency regulation:* the design of Wake-up Radios should adhere to frequency regulations in industrial, scientific and medical (ISM) bands. It should also be adapted to communication standards such as the maximum allowed effective radiated power (ERP) used to transmit the Wake-up signal (WuS).

In the literature, various studies proved the efficiency of low power wake-up radios energy saving. In [54], the authors studied the design (from physical to media access control) and utilization of passive wake-up radios in IoT applications. This review also discusses the limitation of wake-up radios such as the short communication range, the high latency, lack of standardization, mobility as well as contention and channel access. In [50], the authors proposed GREENROUTES, an energy-aware cross-layer routing protocol for wake-up radio-based green networks. This protocol selects the relay nodes based on their distance in hops from the sink ans uses semantic addressing to enhance capabilities. Since wake-up radios are sensible to the distance between nodes, it would be interesting to see if this protocol is efficient in case the nodes are distantly distributed. The authors in [51] analyzed Bluetooth Low Energy (BLE) beacons scenarios in IoT applications and discussed the benefits of integrating wake-up radios in the BLE protocol stack which can help both reduce the time to contact all the beacons and also reduce the current consumption.

Low power wake-up radios networks still suffer from the

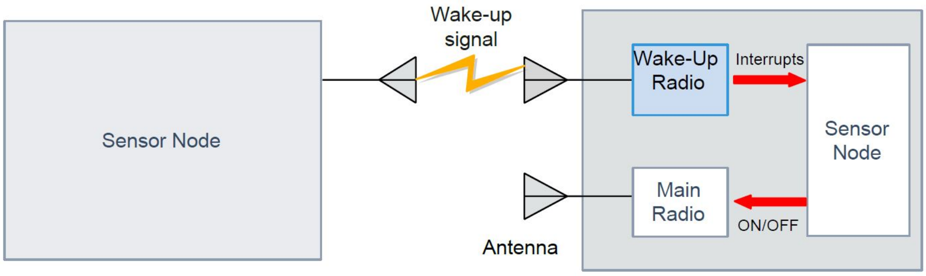

Figure 4: Concept of Wake-Up Radio

limited range of their components. This is why, in [52], the authors tackled the wake-up radios limited range issue and proposed a design and implementation of long range low-power wake-up radio for IoT devices that increases the lifetime of the devices and reduces the power consumption and overall cost in a large scale deployment. Another approach was proposed in [53] to improve the energy efficiency and communication range of wake-up radios in IoT systems. The proposed approach consists in applying error correction codes on wake-up signals. Since wake-up radio suffer from short range capability and low signal sensibility, wake-up radio commonly misinterpret the wake-up signal which leads to performance degradation of the system. Code correction on wake-up signals constitutes an efficient solution to improve the robustness and sensitivity of wake-up devices.

2. *Duty-cycling:*

Duty-cycling, also known as 'sleep schedule', is considered one of the most effective ways of saving energy and extending networks lifetime. Duty-cycling algorithms are used to reduce the node's battery consumption by alternating between sleep and wake-up modes. The node is usually set in a low power mode and only wakes up when needed (e.g. data reception, radio transmission). Those algorithms usually fall under 3 categories: topology control protocols, sleep/wake-up protocols and MAC protocols with low duty-cycles.

Duty-cycling have been studied broadly and due to its constant relevance, several recent works on duty cycling and its impact on the energy consumption of IoT networks have been proposed. In [55], the authors provided a qualitative and quantitative comparison between the families of asynchronous duty-cycling methods, their characteristics and the most suited Green IoT applications for each of them. Asynchronous duty-cycling methods undergo an excessive transmission energy consumption while waiting for the receiver wakes up in addition to the multiple unicast transmissions that not only consume energy but can also lead to a network congestion. In [56], the authors proposed an algorithm to optimize the duty-cycle duration of low-power IoT devices equipped with energy harvesting circuits in Wi-Fi based IoT networks. This solution use an optimal weighting moving-average filter to predict the harvested energy and find the optimal weighting factor to estimate the duration of the off period for IoT devices. The devices will exploit the off periods to harvest enough energy for the data acquisition. Finally, in [57], the authors proposed a modified duty cycling efficient path planning algorithm for an IoT-based precision agriculture system. The proposed duty-cycling algorithm is performed on the data transmission phase and the path planning algorithm studies all the path and chose the shorted path. This solution proves to be effective even with the a high number of devices. However, since the solution's performance depends on the clusters, it would be interesting to optimize the cluster organization in order to reduce the overall energy consumption.

4.2.2. Energy Efficient Data Collection

Millions of IoT devices are deployed in intelligent applications like smart homes, smart transportation, and so forth. These devices generate huge amounts of data. In order to communicate its data to the base station or to his neighbours, an IoT device will consume large amounts of energy. Moreover, IoT networks are usually constituted of a large number of devices that have limited batteries. Once emptied or depleted, those batteries are often difficult to replace especially if the devices are placed in an isolated or a difficult to access position. One promising solution is to collect the generated data and communicate it in an efficient way to reduce the transmission energy cost. Several data collection approaches have emerged in order to reduce the energy consumption, delay and maximize the network lifetime [63].

1. *Data Aggregation approach:* This approach consists in reducing the number of transmission in a network and remove redundant and duplicated transmission of data. Data aggregation is a the procedure of one or a number of nodes that gather data from other nodes for a period of time, aggregate them and transmit the aggregated result. In [63], the authors divided the data aggregation techniques into three classes : tree based, cluster based and centralized based. In [58], the authors presented a systematic review on the data aggregation mechanisms for IoT and presented a detailed comparison of the techniques used in each class. The authors found out that tree-based techniques offer low energy consumption, high network lifetime and great scalability compared to the other techniques while cluster-based techniques offer low traffic and high fault tolerance. On the other hand, centralized techniques focus mainly on security aspects. The latency, network lifetime as well as device heterogeneity should also be considered in data aggregation techniques. In [59], the authors did a review on tree-based data aggregation techniques. The tree architecture is composed of nodes structured in the form of a tree. A tree contains leaf nodes and forwarding nodes. The authors found out that tree-based aggregation consumes less energy than clustering and grid-based aggregation. However, in a tree-based approach, the failure of a intermediate node affects the whole topology and disturbs the network activity. In [60], the authors proposed a cluster-based data collection technique that uses a sensor based cluster formation algorithm to elect the controllers and handle the different types of sensors. This algorithm is used alongside a multi-tier aggregation function. This solution allows us to extend the network lifetime, maximize the coverage and eliminate redundant data at the controller. However, using these structures can have major drawbacks. For example, tree and cluster structures increase the vulnerability of the network and make it less secure. They also do not take into consideration sleep and transmission latency. In [61], the authors proposed a centralized-based data aggregation for IoT which gathers data and sends it to a centralized IoT gateway. This method also proposes an efficient sleep scheduling method along with data aggregation in order to ensure data consistency in the network. Compared to the tree and cluster structures, the centralized structure is more secure. However, it has low fault tolerance.

2. *Probability based approach:* The probability based approach allows us to save energy by using approximation models to find correlation between data. The goal of probability based solutions is to predict the value of the sensed data. In [62], the authors proposed a Bayesian inference approach that allows us to avoid the transmission of highly correlated sensor data and reduce IoT networks energy consumption. This approach was applied to a hierarchical architecture with smart devices and data centers and proved to reduce the number of transmitted

data with good information accuracy in three different scenarios. In general, it is difficult to implement since the devices that help achieve the probability based approach can be increasingly complex and the models are not optimal considering the high correlation between the devices data.

3. *Compressive sensing based approach:* Compressive sensing consists in compressing the collected data and reduce the quantity of data sent throughout the network. Compressive sensing help reduce the size of the sensory information matrix as possible to reduce information and communication redundancy. According to [63], compressive sensing approaches can be divided into three categories : Conventional compression, Distributed source coding and Distributed compressive sensing. In [64], the authors presented a review on data compression techniques from different perspectives such as data quality, coding schemes, data type and applications. Data compressing techniques are described by their compatibility, representation efficiency, computational complexity and memory management. Data compressing solutions should optimize these characteristics in order to enhance the efficiency of IoT networks and reduce the devices complexity. In [65], the authors proposed a clustering routing protocol based on energy efficient compressive sensing that finds the optimal size of a cluster, the optimal distribution of cluster heads and also alleviate the "hot spot problem". This solution reduces efficiently the overall energy consumption of the network and extend its lifetime. In this case, there is a temporal correlation between data which means it would be interesting to use a predictive approach in order to reduce the energy consumption resulting from the spacial-temporal correlation. In [66], the authors employed distributed source coding between two node in a NOMA pair to optimize the performance and minimize the energy consumption in resource-constrained cellular IoT networks. This solution focuses only on mobile broadband applications, where transmissions typically occur in the downlink with full-buffered traffic.

4. *Mobility based Data Collection:* Recently, mobile data collection approaches have been widely used as a mean to develop energy efficient IoT networks and extend their lifetime. Mobile data collection allows battery-limited devices to save their transmission energy and thus extend their lifetime. Mobile data collection can be achieved by three methods. The first method consists in using static sensor nodes and a mobile sink that will collect data from these nodes when they are sufficiently close to it. The second method consists in having a static sink and mobile nodes. Since the nodes can move, they improve the network coverage and decrease the number of nodes needed (e.g. we can have less sensors in the network since one sensor can move and cover other areas of the network). This strategy has been studied widely in the recent years the number of mobile is increasing. The third method consists in having mobile sensor nodes and a mobile sink.

   There have been various studies that focused on energy efficient mobility-based data collection in the literature. In [67], [68] and [69], the authors studied the use a mobile sink (UAV) with fixed nodes and proposed a solution that optimizes the UAV trajectory in order to ensure an energy efficient data collection. In [70], the authors proposed an algorithm for a distributed bus-based data collection to maximize the lifetime and throughput of WSNs. On the other hand. Researchers also studied the use of a mobile nodes with a static sink. In [71], the authors proposed a solution based on the Internet of Vehicles that allows traffic data gathering architecture with an efficient sink node selection. This solution shows only certain vehicles and paths should be selected to reduce the network energy consumption. As shown in the latter works, mobility-based data collection is a very promising energy saving technology if the mobile sink has a low carbon footprint and is provided with an optimized trajectory which constitutes a challenging research area.

4.2.3. Discussion

The energy saving techniques presented in the previous section are used to reduce the energy consumption of IoT devices as much as possible. In Table 6, we summarize the energy saving techniques presented previously and highlight the pros and cons of using these techniques in IoT networks.
In case of sleep/wake-up schemes, both duty-cycling and wake-up radios considerably reduce the nodes energy consumption. While wake-up radios is an on-demand sleep and wake-up scheme, duty cycling schemes can be divided into three categories: on demand, asynchronous and schedule rendez-vous. Accordingly, wake-up radio schemes are able to reduce the idle listening and overhearing that duty-cycling may suffer from. However, it has a limited communication range, a high deployment cost and can suffer from high interference. Duty-cycling, on the other hand, in addition to idle listening, overhearing and over-emitting can also struggle with high sleep latency (e.g. sending data to a node who is not ready to receive data) and data transmission latency (e.g. waiting for the next wake-up phase to send data). Choosing either wake-up radios or duty-cycling depends essentially on the network needs and requirements.

Energy efficient data collection approaches are efficient schemes to reduce the energy consumption of IoT. However, they still have challenges and issues to overcome such as security and latency issues for cluster-based and tree-based data aggregation or the hardly achievable sensory data sparsity in data compression. Mobility based approaches can also be subject to data loss and energy starvation if the system policy used is not well defined.

5. Recent Advances in IoT ecosystem Energy Management

In order to achieve Green-IoT, several new approaches for energy management have been explored by the researchers to reduce the energy consumption of the different components of the IoT infrastructures from data centers to the IoT nodes. These developments emerged with the exploitation of new communication paradigms like 5G and the rapid growth of technologies such as artificial intelligence, cloud, etc. In this section, we will present the recent advances in energy management for IoT networks ecosystem. In Table 7, we summarize the energy management solutions studied for cloud, fog and edge enabled IoT networks.

5.1. Energy management in IoT-Cloud Computing

With the start of the IoT revolution, the number of IoT devices has exploded and with it, the amount of data collected by those devices. However, since IoT devices do not possess the computational power to process all of the collected data, cloud computing is considered as a very promising paradigm that provides high-performance computing capability and high-capacity storage to support the ubiquitous need for data collection and processing in IoT networks. Cloud computing allows the battery-dependant IoT devices to offload various tasks to the cloud (e.g. data cleaning) and conserve their energy. Although it can be convenient to use this technology, it is well-known that the cloud servers that host cloud applications are highly energy consuming. Therefore, it is also necessary to reduce the cloud energy consumption by using its resources efficiently. Reducing energy consumption in Cloud computing can also be achieved by the use of low-power devices and the virtualization of services.

In the literature, a large scope of energy saving solutions in cloud computing enabled IoT networks have been studied. In [72], the authors proposed an energy-efficient architecture for IoT that allows the system to predict the sleep interval of sensors-based IoT networks upon their remaining battery level and reduce the energy consumption of sensor nodes and cloud resources. However, this solution is not recommended for application with strict real-time requirements since it is specific to systems with a sleep/wake-up strategy. Various solutions proposed energy saving in cloud computing by using service com-

Table 6: The Table Shows The Pros And Cons Of The Energy Saving Techniques Discussed In The Survey

Energy Saving Technologies		Pros	Cons
Sleep/Wake-Up	**Wake-Up Radio**	• Reduce the power consumption of battery powered networks • On demand sleep /wake-up • Reduce idle listening and overhearing	• Short communication range • High deployment cost • High interference
	Duty-Cycling	• Reduce the power consumption of IoT devices • On demand / asynchronous / schedule rendez-vous	• High sleep latency • Data transmission latency • Idle listening, over-emitting and overhearing
Mobile Data Collection	**Data aggregation**	• Reduces energy consumption • Reduces traffic load	• Risks of high latency • Less secure for the non-centralized approaches
	Probability based	• Predict sensing data • Save transmission energy	• Not accurate • Add communication costs
	Compressive Sensing	• Reduce information redundancy • Save communication energy	• Restricted to non-complex sensor data • Not always feasible
	Mobility based	• Reduce routing distance and transmission costs • High network flexibility and coverage	• High energy consumption to recover dysfunctional mobile nodes • Optimal Path for the mobile node is difficult to find

Table 7: The Table Shows The State-Of-The-Art of Recent Energy Management Approaches For IoT In The literature

Energy Management Approach	**References**
Cloud Computing	[72], [73], [74], [75], [76], [77], [78]
Fog Computing	[79], [80], [81], [82], [83], [84], [85], [86], [87]
Edge Computing	[88], [89] [90], [91],

position optimization. In [73], the authors proposed a multi-cloud IoT service composition algorithm (E2C2). The composition of services is energy-aware and integrates the minimum number of IoT services to meet a user's requirements. This solution outperforms similar algorithms have been previously proposed: All Cloud, Base Cloud, Smart Cloud [74] and COM2 [75]. To further improve service composition solutions, we should take into account not only the cloud providers aggregate energy, but also the energy needed for the service execution. In [76], the authors presented a partitioning method of an application into offloadable and non-offloadable components to reduce the energy consumption and the execution time. This solution offloads components to the cloud however, it requires high network reliability in order to ensure the application well functioning and availability.

Other solutions focused on energy saving using power-aware virtual machine placement in cloud providers. In [77], the authors also proposed a virtual machine placement algorithm in order to reduce the number of active physical machines and reduce their energy consumption while also load balancing between the active physical machines. However, in this solution a static virtual machine placement is done which means once a virtual machine is placement it can not be migrated to another physical machine. In [78], the authors proposed an ant system for dynamic virtual machine placement that reduces the number of active physical machines and reduces the overall energy consumption of the data center. In dynamic virtual machine placement, virtual machines can be migrated from one physical machine to another. Therefore, security strategies should be applied during migration in order to protect private data from hackers' attacks.

5.2. Energy management in Fog Computing

Cloud computing offers a platform and frees businesses and end users from the burden of many specification details. However, it does not constitute an effective solution for latency sensitive applications and often fails to meet their delay requirements. Consequently, Fog computing emerged as a new paradigm that constitutes an extension of cloud computing at the edge of the network rather than a replacement to it. Fog Computing is a highly virtualized platform that provides computing, storage, and networking services between end devices and traditional Cloud Computing Data Centers[79]. Fog Computing platforms are designed to support the mobility, geo-distribution in addition to low latency required in various IoT application (e.g. industrial-IoT). These characteristics make the Fog platforms suitable to support the energy constraints of Green-IoT applications.

Various Fog computing solutions have been proposed in the literature to reduce the energy consumption in IoT systems. In [80], the authors studied the sustainability of Fog Computing and its performances compared to traditional Cloud in terms of power consumption, CO_2 emissions and cost in IoT networks. Fog computing enhances the performance of latency sensitive applications in terms of QoS and eco-friendliness. In [81], the authors identified major features (such as dynamic discovery, configuration, management of devices, multi-protocol support at different layers of the network architecture, mobility etc.) that fog computing platforms need to support toward building sustainable sensing infrastructure for smart city. Fog computing platforms should built in a manner that different applications can use. Such platforms should also offer build-in support for different types of communication and data analytics frameworks in order to implement the different features of fog-IoT platforms. In [82], the authors proposed a solution that allows a number of IoT devices to select a fog instance that will receive their data considering the energy consumption (e.g energy consumed by the transport network, energy to process and store the data, energy to forward the data to the cloud if needed) and the latency (transmission latency, processing latency, forwarding to cloud latency). In [83], the authors reviewed the AI based application placement solutions that address latency, resource utilization and energy consumption issues in fog enabled IoT networks. Fog application placement solution focus mostly on achieving efficient load balancing methods. Machine learning and more specifically, reinforcement learning algorithms, are widely used and combined with evolutionary algorithms in order to solve the fog application placement problem. Algorithms can be combined to cover each others' weaknesses and achieve challenges such as security, privacy, availability, etc. In [84], the authors proposed an energy efficient fog-based IoT scheme that reduces end-devices energy consumption for industrial IoT by reducing their transmission. This scheme uses an MQ Telemetry Transport broker to predict future data measurements through prediction techniques, operate as gateway and offload expensive data processing from the Cloud to the Fog.

In order to reduce the energy consumption in fog-based IoT networks, various fog computing models were proposed. In [85], the authors proposed a linear fog computing model to reduce the total energy consumption. Although linear models are simple and useful they are only suitable for IoT networks with few number of sensor nodes. Consequently, in [86], the authors proposed a tree-based fog computing model that supports a large number of IoT devices and reduces the total electric consumption compared to the Cloud Computing model. Finally in [87], the authors proposed a distributed (online) learning model on the sensor device. The model is created by mining the collected data that approximate the data stream behavior and then transmitting only the updated model parameters to a fog computing system. This solution saves energy in IoT devices by preventing unnecessary uplink transmission.

5.3. Energy management in Edge Computing

With the increasing number of IoT devices, the data produced by those devices is also escalating explosively. Processing efficiently those data then becomes a necessity in Green-IoT. Therefore, edge computing technologies emerge as a very attractive solution for energy management in IoT as they bridge the gap between the limited capability of low-powered devices and their computational demands. Edge computing allows the workload to be offloaded from the cloud to a location closer to the source of data that need to be processed. It offers the possibility to downstream data on behalf of cloud services and upstream data on behalf of IoT services. It consequently has the potential to extend the lifetime of battery constrained IoT devices, reduce the network traffic, increase the bandwidth, improve the privacy and achieve a considerable energy and communication delay saving.

Different approaches have been proposed to achieve energy saving in Edge computing based IoT networks. Energy efficiency using edge computing can be achieved through different schemes : from offloading strategies to data reduction schemes as well as the efficient management of IoT devices and applications. In [88], the authors tackled the scalability and energy consumption challenges that IoT faces by proposing a novel architecture including the cloud, mobile edge computing and IoT. It includes a framework which develops a selective offloading scheme to reduce the energy consumption of IoT devices and the overhead of edge devices. However, this architecture needs to overcome many challenges related to nodes identification by the virtual machines (especially if they change location) as well as the nodes and virtual machines migration. In fact, if a mobile node changes its location, the system should find an efficient strategy that can either migrates the virtual machine or not based on the QoS requirements of the application. In [89], the authors proposes a reinforcement learning based offloading scheme for IoT devices with energy harvesting. IoT devices select an edge device and their offloading rate according to their current battery level, the previous radio transmission rate to each edge device, and the predicted amount of harvested energy. This solution also includes a deep reinforcement-based offloading scheme to further accelerate the learning speed. In [90], the authors also combined Edge Computing with deep reinforcement learning in an IoT-based energy management system to reduce the energy consumption in a smart home context. The proposed solution consists in an offline and an online phase. During the offline phase, a deep neural network is trained and a deep reinforcement learning model based on Q-learning is built and exploited

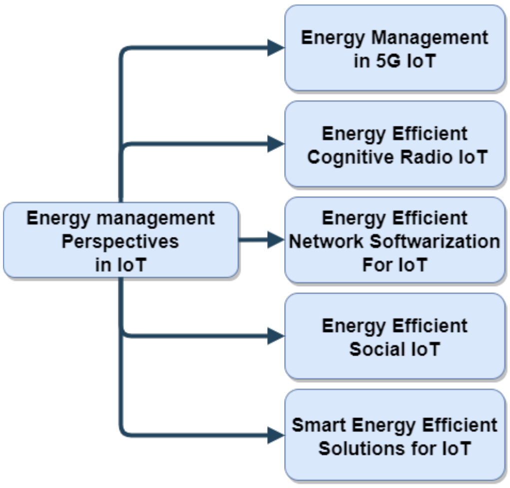

Figure 5: Research Perspectives in energy management for IoT

during the online phase. The proposed solution proves to reduce the energy cost. Such solutions can be proposed to reduce the energy consumption of smart homes in a smart city context. In [91], the authors focused on compressing the data collected by the edge device before their transmission. The proposed solution is based on an error-bounded lossy compressor designed for high performance applications with high data production. The proposed compression algorithm proved that the extracted data produced similar classification accuracy as the compressed data.

6. Research Perspectives in IoT Energy Management

In this section, we will discuss the use of approaches like social IoT 5G-IoT and network softwarization as well as artificial intelligence and Cognitive Radio IoT in order to reduce the global energy consumption of IoT networks. We will also present the most recent solutions proposed for this purpose. In Table 8, we summarize the papers studied for each approach.

6.1. Energy management techniques in 5G IoT

With the emergence of 5G IoT, up to 120 billion devices will be connected all over the world. In order to meet the intense user demands, the devices will not be limited to smart phones but also home appliances, cars and other devices and will contribute to build a smart society. 5G IoT also claims a data rate increase up to 10 Gb/s and uses multiple technologies (e.g. massive multi-input multi-output (MIMO), small cells, beam forming, etc.) in order to support the tremendous number of users. Consequently, 5G IoT suffers not only from spectrum efficiency but also energy efficiency problems that are causing negative effects on the environment and human health. This exponential growth has raised the energy consumption and carbon footprint of those networks to alarming rates which led both the industry and academia to turn towards green 5G communications.

In the literature, various studies discussed the importance of energy efficiency in 5G networks. In [92], the authors presented an overview of energy-efficient techniques for 5G networks covering resource allocation, network planning, network deployment, hardware solutions, etc. In [93], the authors presented a detailed survey on energy efficient cellular networks and proposed a spectrum sharing solution for prolonged battery life in IoT networks. In [94], the authors provided an overview of several recent solutions for the wireless powering of devices exploiting either near-field or far-field techniques. These techniques are expected to have a leading role in the realization of 5G-IoT networks. In [95], the authors proposed a probabilistic decay feature-based solution which focused on the energy consumption of spectrum sensing for IoT devices in 5G networks. In [96], the authors proposed an integrating and energy efficient system model for 5G-IoT that uses a massive MIMO array to replace the single remote antenna and cellular partition zooming (CPZ) mechanism as a select-and-sleep mechanism, shortening consequently the distance between the components and reducing the number of routers.

6.2. Energy Efficient Cognitive Radio IoT

With the high number of IoT devices connected to the internet, the frequency spectrum used by those devices to communicate are getting crowded. Cognitive radio is an approach that aims to improve the usage efficiency of the radio electromagnetic spectrum by using all available frequencies. The

Table 8: The Table Shows The State-Of-The-Art of Recent Energy Management Approaches For IoT

Energy Management Approach		References
Energy Saving In 5G-IoT		[92], [93], [94], [95], [96]
Energy Efficient Cognitive Radio IoT		[97],[98], [99], [100], [101]
Energy efficient network softwarization		[102], [103], [104], [105], [106],[107],[108]
Energy Saving In Social IoT		[109], [110], [111], [112], [113], [114], [115]
AI-based solutions	**Machine learning**	[87],[116], [117], [118], [119], [120], [121], [122],
	Deep learning	[90], [123], [124], [125]
Application-based energy management		[126], [127], [128], [129], [130], [131], [132], [133], [134]

cognitive radio is an intelligent wireless communication system that can be programmed and configured dynamically. It is built on a software-defined radio which is aware of its environment and uses the understanding-by-building methodology to learn from the environment [97]. It automatically detects the available channels in the wireless spectrum and accordingly adapts its transmission and reception parameters in order to ensure communication reliability and efficient utilization of the radio spectrum.

Recently, the integration of cognitive radio and IoT have been widely studied as a potential solution for the bandwidth scarcity and devices high demand of uninterrupted connectivity. Compared to traditional IoT, spectrum sensing may consume much energy and reduce the transmission power of the network. Thus, reducing energy consumption in cognitive radio networks remains one of the most important challenges in IoT networks energy management. In [98], the authors proposed an energy efficient protocol for cognitive radio IoT that reduces the number of handshakes, avoid re-transmission for reliable data communication and thus reduces communication time and enables energy transmission with high throughput. The reduction in communication time reduces considerably the energy consumption of the network. Other solutions focus on reducing the energy consumption using optimization algorithms. In [99], the authors proposed an algorithm for joint time and power allocation optimization in green cognitive radio networks while in [100], the authors focused on optimizing resources and sensing time in green cognitive IoT. The solution consists in having two groups of IoT nodes alternate between spectrum sensing and energy harvesting in order to compensate sensing energy consumption. The authors in [101], proposed an algorithm to optimize the power allocation and sensing time during imperfect sensing in cooperative cognitive radio networks. Cognitive radios resolve the problem of high spectrum requirements, reduce waiting time and thus allow devices to consume less energy. On the other hand, cognitive radios may face interference issues between secondary and primary users and may also struggle to compromise between a good QoS and energy efficiency.

6.3. *Energy efficient network softwarization for IoT*

IoT connects billions of devices to provide a variety of services (smart homes, smart agriculture, industry 4.0, etc). In order to achieve these services, IoT devices employ various protocols, communication ways, and format of data. The diversity and heterogeneity of IoT data and devices compared to traditional networks in addition to the need of security, privacy, storage and processing means that IoT networks require dynamic solutions for management, configuration, and flow scheduling solutions. Network softwarization in the form of Software Defined Networks (SDN) and Network Function Virtualization (NFV) have emerged in order to overcome the previously discussed challenges.

Networks softwarization consists in transforming telecommunication processing to a software-based environment. It is based on SDN which separates the control plane of the network and the data plane and thus separates the control from the forwarding in the network. The IoT network devices are employed for forwarding the data while the network controllers define the forwarding policies for the devices. These controllers can be organized in a centralized manner or in a hierarchical manner in order to prevent the controller from becoming a single point of failure and enhance the system's fault tolerance [107]. SDN integrated IoT can offer smart routing and load balancing as well as intelligent network traffic management and analysis. SDN can also provide a global view of IoT networks and improve the scalability and security of the networks. Network softwarization is also based on NFV which decouples the functions of network from the network hardware and runs it as virtual machines on containers. Network softwarization schemes such as NFV aim to replace energy consuming network hardware and improve the performances and capabilities of IoT systems. However, it is important to mention that these network functions are often run on servers which are the predominant energy consumers. Then, how does network softwarization impact the overall energy consumption of IoT networks and how can we reduce and optimize its energy consumption?

To this end, various works studied the energy consumption in the network softwarization field. In [108], the authors surveyed SDN-based solutions to improve IoT networks and describes SDN as a solution to IoT challenges focusing on energy saving, network management and mobility. In [104], the authors proposed an SDN-enabled routing protocol that not only efficiently utilizes the limited bandwidth cost to reduce the energy consumption but also achieves the QoS requirements for an industrial IoT network while in [106], the authors proposed a cluster architecture using blockchain-based SDN controllers with distributed network management for IoT devices that provide a secure and energy-efficient mechanism for IoT devices in an SDN domain using a routing protocol. Numerous authors focused on reducing the energy consumption of SDN and NFV enabled data centers and thus, reducing the energy consumption of the whole IoT system. In [102], the authors proposed an open stack based solution to enable policies that enforces constraints in the system with periodic event monitoring and dynamic resource management to minimize energy consumption in NFV data centers. In [103], the authors proposed an energy consumption control solution in SDN-based cloud data centers using the integration of virtual machine migration based on mixed single-parent genetic algorithm. Various SDN solutions achieved energy efficiency through energy efficient routing protocols.

6.4. Social IoT for energy management

Social IoT is a paradigm that resulted from the integration of social networking concepts into the Internet. Social networks are able to connect a large number of individuals and this characteristic has previously inspired researchers in internet-related works [109]. Similarly to social networks, IoT networks use a variety of technologies to connect a large number of things which made the idea of combining these two concepts not only possible but also advisable. The concept of Social IoT was motivated by popular social networks over the Internet such as Facebook and Twitter. Therefore, it has attracted scientists and researchers in E-business, E-learning, sociology, psychology and networking. It has also caught the eyes of researchers in energy management as they consider it a promising solution in green networking.

Since Device-to-Device communication and social network are two essential components in IoT, various authors studied energy management using Social IoT and proposed solutions to enhance the energy and spectrum efficiency in this context. For example, in [115], the authors proposed a social interaction assisted resource sharing scheme for Device-to-Device communication, to improve the utilization of spectrum resources and thus, reduce the energy consumption in Green-IoT networks. The interconnection of IoT devices can also be used to efficiently harvest energy. For example, in [110], the authors proposed a social-aware energy harvesting Device-to-Device communications architecture that integrates energy harvesting technologies and social networking characteristics into Device-to-Device communication to improve the spectrum and energy efficiency for local data dissemination in 5G cellular networks. In [111], the authors also worked on using social interaction in Device-to-Device communication but in this case to improve the efficiency of data exchange, sharing and delivery reducing thus, the energy consumption in the network. In [112], the authors proposed an energy efficient Cyber-Physical-Social system powered by IoT, where wireless network virtualization over SDN was adopted to enhance the service operation and the system management. In [113], the authors propose an efficient pervasive interconnection technique to process and share information in IoT environment based on the human's social network and the device's sociality. In [114], the authors studied the use of smartphone sensors to contribute to smart social spaces as well as the energy consumption of femtocell, a potential communication technology for the realization in 5G-IoT.

6.5. Intelligent energy management techniques for IoT

IoT networks are composed of physical devices such as vehicles, houses and any other item enhanced with sensors and software that enable data collection, distribution and analysis. However, due to the high number of IoT devices and their small sizes, they do not possess the computational power to process all the data collected hence, machine learning and big data technologies are efficient approaches to develop intelligent solutions to the collected data management.

Big data technologies allow the collection and analysis of large amounts of data while machine learning studies algorithms and statistical models based on patterns and inferences that systems use to meet their goals [116]. Likewise, machine learning is a very reliable and robust approach, therefore, it is largely used in real-time applications. It is considered ideal for learning-based problems and is capable of identifying the background and characteristics of such problems to learn from them and execute actions based on the knowledge acquired thus increase system performances.

Due to the high number of IoT devices, the energy consumed by IoT devices is huge. In addition, the world we live in faces a huge environmental crisis with climate change and high rates of air pollution, water pollution, etc. Reducing energy consumption in IoT networks is, then, one of the greatest challenges we might face. Researchers can exploit machine learning and intelligent solutions in order to predict energy consumption in IoT networks and applications.

Various solutions have been proposed in order to reduce the energy consumption of IoT devices. However, those solutions are usually static, limited to a certain context and do not include taking smart and intelligent decisions. For example: in case of energy management of home appliances consumption, various optimizations solutions have been proposed. However, those solutions are depending on a certain context and do not consider a change of habit for the in-habitant. This is why, machine learning has emerged as promising approach to develop intelligent solutions for energy efficiency in smart homes as they are able, using smart meters data, to not only reduce the energy consumption but also adapt the decision making depending on the in-habitants' habits. In fact, it would be interesting to exploit machine learning in order to adjust transport scheduling depending on air pollution or action depollution mechanisms if sensors detect a high pollution rate in water, etc. Hence, many researchers turned towards achieving Green-IoT at different network layers using intelligent solutions like machine learning and deep learning that proved their efficiency in other fields.

Machine learning and deep learning, two Artificial Intelligence (AI) approaches, are often confused as deep learning is considered a part of machine learning but, we believe is important to differentiate them as they are two concepts used in different contexts and application fields.

Table 9: The Table Shows The Pros And Cons Of Intelligent Energy Saving Techniques

Intelligent Energy Saving Techniques	Pros	Cons
Machine Learning	-Help identify trends and patterns -Performances improve over time	-Consumes energy while running the algorithms -Algorithms become obsolete when the data grows -Irrelevant and invaluable data can cause bad results
Deep Learning	-Ideal for complex tasks -Supports large amounts of data	-Bad quality data leads to bad results -Opacity of neural networks -More data security

Machine learning can be defined as algorithms that provide a system the ability to automatically learn and improve its performances. Machine learning algorithms learn from data or experiences and apply what they have learned to make informed decisions. They usually involve human intervention to give feedback to the algorithm. Machine learning algorithms are often categorized as supervised or unsupervised learning. Supervised learning uses the experiences learned from past data and apply it to new data using labeled examples to predict the future actions or events, while unsupervised learning uses unlabeled and unclassified data and helps the system find all kinds of unknown patterns in data. Another category of machine leaning is semi-supervised machine learning which uses both supervised and unsupervised learning. Typically, those algorithms use a small amount of labeled data and the rest is usually unlabeled data. Semi-supervised algorithms decrease the labeling effort and increase the learning accuracy of the system. Finally, reinforcement learning is an approach in which the learning methods consist in interacting with the environment by taking actions and receiving rewards or errors. Within a specific context, this method maximizes the system's performances and automatically determines its ideal behavior.

Deep learning algorithms are an evolution of machine learning algorithms as they use a programmable layered structure of algorithms called an artificial neural network. These artificial neural networks enable systems to make accurate decisions without human intervention. Deep learning differs from the other machine learning algorithms as it is able to accomplish complex tasks using unstructured data, process a large amount of data and learn efficiently without human intervention. In what follows, we will present machine learning and deep learning based solutions employed to reduce the energy consumption of IoT networks.

6.5.1. Machine Learning-based Energy Saving techniques

With the emergence of IoT and the exploding number of IoT devices, the volume of the data generated by IoT systems also increases considerably. Consequently, machine learning techniques have emerged to use the data generated by IoT devices and make IoT application more intelligent. However, due to the high number of IoT devices, the energy consumed by those devices has also increased considerably, thus, energy saving has become a priority for IoT systems designers and end-users. This motivated researchers to study the use of machine learning in order to create green smart and sustainable IoT-network applications.

The amount of works concerning the use of machine learning to achieve energy saving is large. To help reduce the energy consumption, machine learning can be used in energy saving IoT applications such as Smart Buildings [117], [118], Smart Energy [119],[120], Smart Water [121]. Other works focus on saving energy by efficiently transmitting data and reducing the number of transmitted packets [87]. While in [122], the authors focused on energy efficient mobility prediction using machine learning. This shows if the data features are known and with the available datasets, machine learning algorithms prove to be an interesting solution that can be used and adapted to different aspects of energy saving in IoT networks.

6.5.2. Deep Learning-based Energy Saving techniques

Deep Learning is a promising approach for energy management in IoT networks. As shown in Table 9, it differs from machine learning as it provides better performances with large scale data. Deep learning algorithms are self-directed on data-analysis and can automatically extract new features for problems in contrast to machine learning algorithms which depend on the extracted and already identified features.

Deep learning has been used in several works related to energy saving. In [90], a deep reinforcement learning-based energy scheduling was proposed to deal with uncertainty and intermittence of energy supplies. In [123] and [124] a deep reinforcement learning approach was proposed to obtain an energy management strategy for a hybrid electric vehicle. On the other hand, in [125], a deep Q-learning based energy management strategy for power split Hybrid Electric Buses is proposed. As shown in the works presented previously, deep learning can be used in numerous energy saving applications. However, it is more suitable for large scale applications that require constant learning and that needs to adapt to the state of its environment.

6.6. Application-based energy management

IoT has revolutionized the way we live. However, IoT technologies face several challenges such as the increase in energy consumption and carbon footprint of IoT nodes. Therefore, IoT applications must be smart, eco-friendly and sustainable and with the recent development of Green IoT, it has become a tool towards achieving green and sustainable societies. Various IoT solutions have been proposed where IoT is an enabler for greening several fields of our society such as waste management, retail and logistics, smart streets, etc. For smart waste management, the authors in [126] proposed a smart waste management system where the waste level in waste bins is communicated and an optimized and energy efficient route is proposed to the workers. In [127], the authors proposed a smart street framework where streetlights are powered by solar panels and are efficiently monitored and maneuvered by IoT. The streetlights operate at different intensities depending on the traffic flow rate and the absence or presence of sunlight and vehicles. In the proposed solution, streetlights are also equipped with sensors to help monitor air quality.

Throughout the years, it has also been proven that traditional infrastructures that help simplify human beings daily lives (e.g. public transportation systems, home appliances, cars, factories, etc.) waste a tremendous amount of energy. Therefore, in order to continue using these vehicles and infrastructures without draining our planet's energy resources, greening using IoT becomes a top priority and constitutes a step towards achieving green and sustainable societies. Consequently, various solution have been proposed as alternatives to traditional and polluting applications. In [128] the authors discussed the use of Intelligent Transportation Systems to achieve energy saving and what changes both consumers and decision-makers should take in order to reduce the energy consumption of public transport systems. In [129], the authors studied the use of renewable energies to power public transport (buses) and reduce the energetic dependence on fossil fuels by replacing diesel vehicles with hydrogen-powered vehicles. Numerous works specialized in energy management for trains and railways station such as [130] and [131]. Personal vehicles are also concerned with energy management. In [135], the authors proposed a a solution based on fuzzy logic aimed at prolonging the battery life of electric bikes. The use of electric bikes (e-bikes) is particularly interesting in IoT networks as they can be used as mobile node for energy or data transmission. Reducing energy consumption in buildings also caught the eye of researchers [132]. For example, in [133] and [134], the authors proposed solutions to minimize energy consumption of homes and building appliances while causing the minimum discomfort to the user. In [133], the authors proposed a hybrid solution based on three heuristic algorithms for home energy management in a smart building while in [134], the authors proposed an approach to both physical and logical organization of an active demand side management system for building-integrated prosumer microgrids based on IoT and standard building automation and control systems (BACS).

7. Discussion

In this section, we will present recommendations and indications to IoT system designers on which techniques presented in our survey can help achieve the requirements of an IoT application in an energy efficient way. The application fields of IoT in a single domain are diverse thus, the requirements can differ from one application to another in the same field. However, a number of these techniques can be used for different applications. For example, using battery-less devices with backscatter communications, simultaneously transmitting power and information with SWIPT, in addition to periodically alternating between sleep and wake-up states for IoT devices with duty-cycling and wake-up radios that can be combined with machine learning techniques to optimize the sleep and wake-up time. These techniques are very promising and are use in scenarios where the device do not need to be constantly active. 5G technology is integrated with IoT networks in order to boost the communication and response time as well as the capacity of IoT networks. Security is also crucial for IoT applications that use private and critical data such as smart homes, healthcare and industrial IoT. IoT system designers should consider security at different layers of the network with security protocols as well as network softwarization that not only allows to save energy by replacing physical security devices but also to have powerful security mechanisms. Green energy sources also need to be exploited for various applications in order to power the devices and ensure the availability of the devices and real-time data.

7.1. Smart Home

IoT is drastically transforming how households are managed. Devices and home appliances are equipped with communication interfaces and are remotely and automatically controlled in order to offer a comfortable experience for the inhabitants. In this regard, smart homes services need to be available at any time and with low latency. Therefore, processing data at edge, fog and cloud level allows to have a quick response [136]. Task offloading at different levels of the platform also enhances the availability of the service and allows a quick recovery in case one of the components stops working [137].
If smart home sensor data are communicated to the edge, fog or cloud for processing and since communication costs more energy than local computation, energy efficient data communication schemes need to developed for smart home through lightweight protocols, data reduction, data aggregation schemes [138] and social IoT [139] to exploit the interconnection between the devices to find energy efficient communication routes. Smart homes solutions should also be context-aware and flexible thus, these applications can use machine and deep learning techniques in order to adapt to the user's needs and reduce the energy consumption [140].

7.2. Agriculture

IoT was introduced in agriculture to improve agricultural yield and quality for the increasing world population. IoT is used to collect real-time information about temperature, humidity and soil and transmit them to a platform where they will be used to monitor the production. IoT devices in smart agriculture applications need to be reliable through weather conditions and available for years without the need for battery replacement. In addition to green energy sources and intelligent sleep/wake-up techniques, energy efficiency in agriculture IoT devices can

Table 10: The Table Shows Recommendations On How To Use The Energy Management Techniques Presented In Our Survey to meet IoT applications requirements

IoT application	Requirements	Techniques	Recommendations
Smart Home	Availability, low latency, EE data communication, data reduction, context-aware, security	Task offloading, data aggregation, social IoT, intelligent smart home solutions	Reduce data transmissions through data aggregation, reduce response time and latency, adapt to the context, use task offloading to enhance fault tolerance
Agriculture	IoT nodes reliability, sensor data management, flexibility	mobile energy transfer, intelligent data collection, data reduction	Exploit moving vehicles to power devices, use intelligent mobile data collection to reduce data transmission, reduce and compress sensor data
Healthcare	Low response time, fault tolerance, node mobility, security	Mechanical EH, mobile energy transfer, social IoT	Use RF wireless charging and mobile energy transfer for mobile node, achieve self-powered IoT devices through mechanical energy harvesting, achieve security and reduce time to response and latency with network softwarization, enhance availability and fault tolerance with social IoT
Industrial IoT	Low response time, availability, security, fault tolerance, flexibility, mobility, devices heterogeneity and scalability	Intelligent sleep/wake-up techniques, intelligent mobile data collection, RF energy harvesting, intelligent mobile energy transfer, CR-IoT, task offloading, network softwarization	Reduce data transmissions through machine learning based data collection and data reduction, reduce response time and latency, optimize spectrum efficiency, employ RF wireless charging and intelligent mobile energy transfer

also be achieved through using mobile vehicles such as tractors as power relays and data sinks and ensure the availability of the application data. A combination of sleep/wake-up techniques techniques and UAV-based mobile energy harvesting is proposed in [141] for a smart agriculture system. Agricultural application are in constant expansion. Therefore, sensor data management is a key challenge that need to be taken into consideration through different devices organisation schemes as well as data reduction and flexible data collection strategies.

7.3. Healthcare

IoT is progressively integrated in healthcare in order to improve the access and enhance the quality of care. IoT healthcare applications aim to achieve excellent healthcare services at affordable costs. IoT in healthcare can be used to monitor a patient behaviour and extract information that will improve well-being, healthcare and patient support. Patients' medical information are critical, this is why healthcare application should protect data with secure transmission protocols. Healthcare IoT application should also offer real-time information about the patient's health condition with low response time which will be possible with the democratization of 5G networks. In order to ensure efficient patient support and services, IoT healthcare services should be available even if one of the components stops working and devices should be able to function through arduous condition for a long period of time (e.g. wearable heart rate monitor). One of the most suitable approaches presented in our survey to meet those requirements is social IoT. IoT devices in healthcare are often mobile, the connection and relationships between these devices can be exploited in order to ensure the availability of critical information and the system's fault tolerance. In [114], the authors used 5G and exploited Social IoT to ensure service availability for smart devices. The social aspect of IoT devices can also be exploited for power transmission between devices [142]. For healthcare IoT applications that use wearable devices, human motion and mechanical energy harvesting can constitute the perfect solution to further increase the devices' and network's lifetime [143].

7.4. Industrial IoT

IoT has recently made its way to the industry. It refers to the interconnection of all the industrial assets and aims to collect the maximum data from these assets to achieve optimal industrial operations. Industrial applications that are safety-critical and used for control and decision making need to be available and reliable at any time. In order to achieve industrial IoT applications requirements of real-time performance, 5G communication technologies [144] that offer low latency can be combined with CR-IoT [145] to satisfy end-to-end deadlines of the tasks and optimize the frequency spectrum utilization and thus, reduce the waiting time. Edge and Fog computing can be used to perform energy-hungry computation at the edge of the network (as in [146]) with low latency instead of handling them on the cloud which induces a longer transmission time and a higher energy consumption. With the large amounts of data generated in industrial IoT applications, an compromise must be made between the high availability of industrial IoT and the high energy consumption of data transmission. Therefore, IoT devices data should be organized and reduced through data aggregation and reduction techniques presented in our survey to reduce the transmission data energy consumption and latency in industrial IoT applications. Similarly to smart homes, industrial IoT applications should use artificial intelligence in order to offer a flexible and context-aware experience and exploit mobile devices in order to power other devices through intelligent mobile energy transfer strategies [147].

8. Conclusion

With the constant need of human being to have a safe, comfortable and stable environment, Green IoT emerged as a key and hot technology. It guarantees a decrease in the energy consumption of IoT. In the coming years, the number of IoT devices will be even higher as big companies (e.g. Google, Amazon, etc) are investing in the sector. Thus, companies and organization should develop IoT solutions from an eco-friendly and energy efficient standpoint. Re-usability and recycling of IoT devices should also be a focal point of the research of Green IoT to avoid the energy resulting from the process of producing new smart devices. Therefore, in order to achieve Green and sustainable IoT, there is a crucial need for new IoT policies and standardization that include the principles of Green IoT.

In our survey, we have focused on gathering a large range of energy management technologies that will help achieve Green IoT systems. We have also discussed recent trends and new perspectives in IoT networks energy management that were not discussed previously in the literature. It is important to mention that other factors like QoS and security can further increase the energy consumption of Green IoT networks. For the longest time, in order to offer the best experience to the user, energy consuming solutions that achieve a good QoS was often privileged to a green solution that could lack in an aspect of QoS. Security is also another energy consuming factor of Green IoT. With the high expansion of IoT networks and high IoT nodes connectivity, the cybersecurity risks increase accordingly. Personal and private data will also circulate through IoT networks. Therefore, it is important to address the cybersecurity issues.

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