Enabling Technologies for Green Internet of Things

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***Abstract*—Recent technological advances have led to an increase in the carbon footprint. Energy efficiency in the Internet of Things (IoT) has been attracting a lot of attention from researchers and designers over the last couple of years, paving the way for an emerging area called green IoT. There are various aspects (such as key enablers, communications, services, and applications) of IoT, where efficient utilization of energy is needed to enable a green IoT environment. We explore and discuss how the various enabling technologies (such as the Internet, smart objects, sensors, etc.) can be efficiently deployed to achieve a green IoT. Furthermore, we also review various IoT applications, projects and standardization efforts that are currently under way. Finally, we identify some of the emerging challenges that need to be addressed in the future to enable a green IoT.**

***Index Terms*—Cloud computing, green Internet of Things (IoT), machine-to-machine (M2M), near-field communication (NFC), radio-frequency identification (RFID), wireless sensor networks (WSNs).**

I. Introduction

THE Information and Communication Technology (ICT) has simplified and automated many real-world tasks. Nowadays, computers are monitoring and controlling various aspects of the physical world. Computers are needed to make different types of electronic devices, operate ships and airplanes, manufacture goods, and all of those computers consume substantial amounts of energy to operate. The energy consumption issue has been receiving increasing attention and is leading to more efficient and sustainable use of resources to avoid global warming and higher energy costs. ICT is not a major contributor to greenhouse emissions but still produces around 2% of the global carbon footprint [1]. Due to emerging ICT scenarios and their demands, it is estimated that by 2020, the average annual ICT contribution will be around 6%–8% [2]. As ICT becomes more pervasive in the different sectors of society, the need for energy-efficient solutions for ICT (also often referred to as green ICT) also increases. Accordingly in [3] green ICT is defined as "the study and practice of designing, manufacturing, using, and disposing of computers, servers, and associated subsystems (such as monitors, printers, storage devices, and communications systems) efficiently and effectively with minimal or no impact on the environment."

The Internet has played a major role in the flourishing ICT sector. Communications over the Internet involve mainly client–server connections. In some scenarios, the server may fulfill the request of many users simultaneously. Traditionally, human users have been the primary producers and consumers of information on the Internet but with the proliferation of billions of devices, this trend has shifted to those devices in recent years. Currently, social networks have revolutionized the way the information is generated and shared among different entities. Society is moving to the next level of information generation and sharing where humans rely on information that machines, such as weather monitoring systems, generate. At the same time, the machine-to-machine (M2M) communication paradigm is also gaining momentum; in such a situation, machines consume the information other machines generate (e.g., upon fire detection, a monitoring system communicates with a sprinkler system to extinguish the fire). This is just a beginning; in the future, everything around us could be connected and be able to sense and cooperatively communicate over the Internet, thereby giving birth to the *Internet of Things* (IoT). The basic idea behind IoT is the pervasive and ubiquitous presence of the things or objects around us, e.g., mobiles, sensors, radio-frequency identification (RFID) tags [4], etc. This leads to the generation of huge amounts of data that need to be stored, processed, and presented in an energy efficient manner. This also requires energy efficient approaches for the data centers.

Considering IoT as potential technology that will change the face of this planet, the U.S. National Intelligence Council (NIC) included IoT among six "Innovative Civil Technologies" that will impact U.S. power grids [5]. NIC foresees that "by 2025, Internet nodes may reside in everyday things, i.e., food packages, furniture, paper documents, and more." Generally, low resources in terms of computation, communication, and energy capacity characterize the things composing the IoT. Accordingly, proposed solutions need to pay special attention to resource efficiency in addition to the obvious scalability problems. Furthermore, as all the devices need to be equipped with additional sensory and communication add-ons, they also require more energy in order to perform their tasks. Keeping in mind various organizations' widespread interest and adoption, the energy demand for IoT will increase exponentially in the future. This necessitates the emergence of green IoT where consideration of energy efficiency is at the core of the design and development of the system. If we do not consider the green perspective of IoT, we may face energy demands that can never be fulfilled.

The main objective of this work is to provide the reader with an understanding of what has been done to enable green IoT ecosystems (key enablers, applications, and standards), what still remains to be addressed and identify the various factors that are enabling this evolutionary process along with their weaknesses and risks.

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II. IoT: Definitions and Architectures

The idea of IoT, where everything is connected is not new, but this paradigm shift has received a lot of momentum lately and many efforts have been initiated toward the realization of IoT. Nikola Tesla in 1926 stated: "When wireless is perfectly applied the whole earth will be converted into a huge brain, …. and the instruments through which we shall be able to do this will be amazingly simple compared with our present telephone." Weiser had foreseen IoT [6] as: "The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it." Also, Neil Gershenfeld in his book [7] "When Things Start to Think" stated: "In retrospect it looks like the rapid growth of the World Wide Web may have been just the trigger charge that is now setting off the real explosion, as things start to use the Net."

Next, we define the common IoT definitions and propose a generic meaning of green IoT to grasp the whole picture.

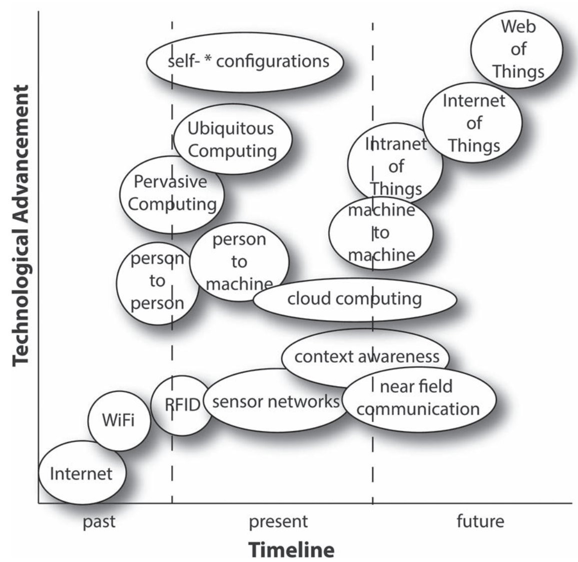

Fig. 1. IoT—A plethora of concepts.

A. IoT Common Definitions

IoT is a "global concept" that requires an extraordinary effort to come up with a common definition [8]. ITU-T defines IoT as follows "In a broad perspective, the IoT can be perceived as a vision with technological and societal implications. From the perspective of technical standardization, IoT can be viewed as a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on, existing and evolving, interoperable information and communication technologies. Through the exploitation of identification, data capture, processing and communication capabilities, the IoT makes full use of things to offer services to all kinds of applications, while maintaining the required privacy." The IoT European Research Cluster (IERC) defines IoT as "A dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols where physical and virtual "things" have identities, physical attributes, and virtual personalities and use intelligent interfaces, and are seamlessly integrated into the information network." The word dynamic depicts the evolving, adapting, scaling, and self-configuring nature of the network. In [9], IoT is semantically described as "a world-wide network of interconnected objects uniquely addressable, based on standard communication protocols." The Auto-ID Labs [10] defines IoT as "the basic counterparts that interlink the real world and the digital world." The CASAGRAS consortium [11] view IoT as follows: "The natural enabling architecture for the deployment of independent federated services and applications, characterized by a high degree of autonomous data capture, event transfer, network connectivity and interoperability." On the other hand, the IP for Smart Objects (IPSO) Alliance [12] and Internet-0 [13] is trying to adapt the current Internet architecture for IoT. According to IPSO, a wise IP adaptation would be to introduce IEEE 802.15.4 into the IP architecture (6LoWPAN [14]) to enable the entire deployment of the IoT paradigm smoothly.

Keeping in mind the aforementioned definitions, one might find it difficult to understand what IoT really means, what constitutes its basic concepts, and what are the social, economical and technical implications that hinder in the deployment of IoT. The reason for today's obvious ambiguity stems from the term IoT itself, which focuses, on one hand, on the network features of IoT (the Internet) and, on the other, on generic "objects" (Things) to be incorporated into a common framework. Fig. 1 depicts the plethora of terminology, concepts, and technologies for IoT along timeline and technological advancements.

B. What Is Green IoT—A Definition

Green IoT can be defined as the energy efficient procedures (hardware or software) adopted by IoT either to facilitate reducing the greenhouse effect of existing applications and services or to reduce the impact of greenhouse effect of IoT itself. In the earlier case, the use of IoT will help reduce the greenhouse effect, whereas in the later case further optimization of IoT greenhouse footprint will be taken care. The entire life cycle of green IoT should focus on green design, green production, green utilization and finally green disposal/recycling to have no or very small impact on the environment [3].

C. Common IoT Architectures

The key design requirements for the IoT architecture are modularity, flexibility, interoperability, scalability, etc. In order to ensure these requirements, an open system is needed. To date, there is no commonly accepted understanding of IoT architecture [8]. We present some of the recent initiatives to develop IoT architecture. The EU FP7 IoT-A Project [15] provides an initial glimpse into the concepts of the architectural reference model. IoT-A defines a layered architecture [see Fig. 2(a)] where the IoT business process is also included to fulfill the stakeholder's requirements. Other layers included are the virtual entity layer, IoT service layer, IoT service organization layer. The security and management layers are common to all other layers. The different architectural layers utilize existing protocols and procedures to fulfill the specific requirements of a given layer. The IoT-A architecture provides the highest abstraction level for the definition of services and promotes a common understanding of the IoT domain.

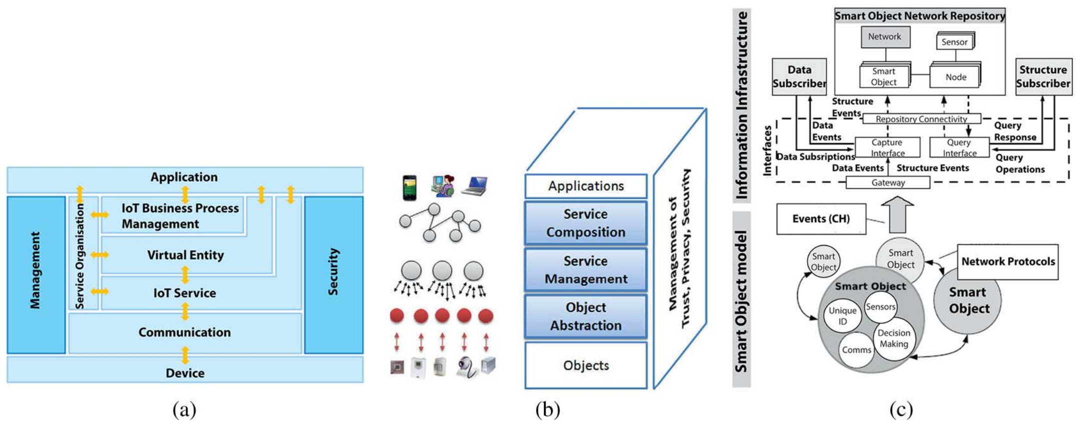

Fig. 2. Different IoT Architectures. (a) EU IoT Architecture [15]. (b) SOA-based Architecture [16]. (c) Smart Object-based Architecture [17].

In [16], another layered model based on the service-oriented architecture (SOA) is presented [see Fig. 2(b)]. The SOA architecture relies on five layers: application, service composition, service management, object abstraction, and physical objects. Alongside these layers, the management of trust, privacy and security is common to all layers. The service composition layer provides the functionalities for the composition of the single service that networked objects offer to build specific applications. On this layer, there is no notion of devices and only the services are visible. The service management layer provides the main functions for each underlying object. The object abstraction layer provides wrapping of a vast variety of heterogeneous objects in order to provide common procedures to access them. In [17], the authors introduced the use of the Smart Object framework to encapsulate RFID, sensor technologies, embedded object logic, ad hoc networking, and Internet-based information infrastructure [see Fig. 2(c)]. Objects inside the networks cooperate to manage their resources and to make complex decisions on data routing, inter-network relationships, event generation, etc. The well-defined user interfaces are introduced to get data with varying degrees of granularity from the objects. The gathered information is stored in an object repository to be shared with other objects using a well-known Publisher–Subscriber model. To the best of our knowledge, there are no IoT architectures that specifically target the green perspective to save energy right from the development stage.

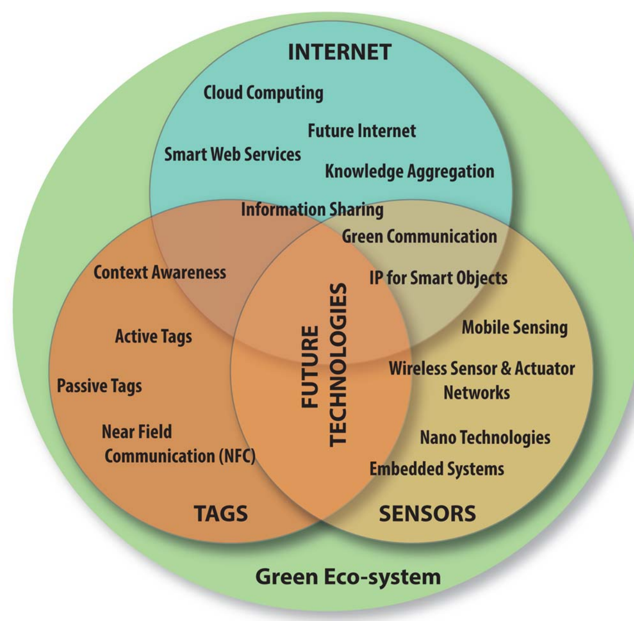

Fig. 3. Green IoT Enablers (adapted from [16]).

III. Enabling Technologies for Green IoT

IoT deployment in the real world is only possible through the cooperation of several enabling technologies, as depicted in Fig. 3 and Table I. Here, we discuss the most relevant technologies and focus on their green aspects that strengthen the green IoT era.

A. Green Tags

"Anytime, anywhere communication" has been a long-time dream and fueling advances in wireless communication technologies. Accordingly today, the ratio between radios and humans is almost one to one [18]. The reduction in terms of size, energy consumption, and cost of the radio lead to its integration in almost every object. One of the promising wireless systems to enable IoT is RFID. RFID consist of several RFID tags and a very small subset of tag readers [19]. An RFID tag is a small microchip attached to a radio (used for both receiving and transmitting the signal) and enclosed in an adhesive sticker [20]. RFID tags include a unique identifier and can store information about the objects to which it is attached. Generally, RFID readers trigger the information flow by transmitting a query signal, and nearby RFID tags respond back. Accordingly, RFID systems do not require any line of sight and can easily map the real world into the virtual world. There are two types of RFID tags: active and passive. The passive tags do not have onboard batteries and harvest energy from the reader signal using the principle of induction. The transmission range of RFID systems is generally very low (a few meters). Various bands are utilized for transmission, i.e., from low frequencies at 124–135 kHz up to ultrahigh frequencies at 860–960 MHz. On the other hand, the active tags include a battery that powers the transmission of the signal and increases the transmission range. Near-field communication (NFC) is one of the latest short-range wireless technologies similar to RFID systems. NFC operates at 13.56 MHz RF band with an operating distance of up to 20 cm. Among RFID technologies, NFC is the most customer-oriented due to

TABLE I
COMPARISON OF GREEN IoT ENABLERS

	Sensing	Processing	Comm.	Range	Data rate	Power	Lifetime	Size	Standard
Green Tags									
Active Tags	Passive	Very Low	Two way	5-10 m	Low	Battery	<5 yrs	very small	ISO18000-6c
Passive Tags	Passive	Not Available	One way	1-2 m	Very Low	Harvested	∞	very small	ISO/IEC18000
NFC	Passive	Not Available	One way	mm-cm	Very Low	Harvested	∞	tiny	ISO/IEC21481
Green Sensing Networks									
Smart Objects	Available	Low	Central	Not Available	Low	Battery	<2 yrs	small	RFC 6690
Mobile Sensing	Available	Moderate	peer-to-peer	100 m	High	Battery	<1 week	brick	Not Available
WSAN	Available	Low	Central	10-50m	Low	Battery	<1 yr	small	IEEE802.15.4
Green Internet									
Cloud	Not Available	Very High	Client/Server	Not Available	Very High	Grid	<10 yrs	Not Available	IEEEP2301-02
Future Internet	Not Available	Very High	Distributed	Not Available	Very High	Grid	∞	Not Available	Not Available
Smart Web Services	Not Available	High	Client/Server	Not Available	High	Grid	<3 yrs	Not Available	JSR-109

the integration of a tag reader into mobile phones allowing easy interaction with smart environments.

RFID plays a major role in applications that help to promote a greener world by reducing vehicle emissions, monitoring the health of wildlife, conserving energy use in buildings, improving waste disposal, etc. Importantly, most examples also have an economic benefit, which will encourage further deployment of RFID systems. Unfortunately, the RFID technology also poses some problems: the tags themselves are difficult to recycle, and their presence makes it difficult to recycle the objects to which they are attached. However, the industry is undertaking a wide range of initiatives to address these problems. One of the simplest solutions is to reduce the size of RFID tags and, thus, the amount of nondegradable material used in their manufacturing. Hitachi has introduced μ-tags that have dimensions of less than 0.4 mm^2. Other initiatives include biodegradable RFID tags [21]–[23], printable RFID tags [24], [25], and paper-based RFID tags [26], [27] in order to provide green solutions for RFID systems.

B. Green Sensing Networks

The fusion of sensing and wireless communication has led to the emergence of wireless sensor network (WSNs) and represent a key enabling technology that helps IoT to flourish. Recently, WSNs have been proposed for variety of applications, such as fire detection [28], [29], object tracking [30] and environmental monitoring [31]. Accordingly, the commercial use of WSNs is expected to dramatically increase in the near future.

Generally, a WSN consists of a large number of static sensor nodes with low processing, limited power, and storage capacity, and unreliable communication over short-range radio links. The sensor nodes are equipped with multiple on-board sensors that can take readings from the surroundings such as temperature, level of humidity, acceleration, etc. Sensor nodes are deployed in an ad hoc manner and cooperate with each other to form a WSN. Typically, a powerful base station known as the *sink* is also an integral part of a WSN. The sink mediates between the sensor nodes and the applications running on a WSN. Currently, many commercial WSN solutions are based on the IEEE 802.15.4 standard, covering physical and MAC layers for low-power, low-bit-rate communications, e.g., IRIS motes [32]. IEEE 802.15.4 does not include higher layer specifications, which are necessary for the seamless integration of sensor nodes into the Internet. In many scenarios, the sensor nodes spend a large part of their lifetime in a sleep mode in order to achieve energy efficiency [33].

Similar to RFID systems, the WSN applications contribute positively to the environment by efficiently using resources and helping to reduce greenhouse effects. The true potential of WSNs can be fully realized only when data communication can occur at ultralow power, and the power supply can be eliminated. Doing so requires a true battery-free wireless solution that can utilize energy harvested directly from the environment. Energy harvesting mechanisms [34]–[36] include those that can generate power from the sun, kinetic energy, vibration, temperature differentials, etc. Eliminating batteries will minimize exposure to the toxic substances within batteries and pave the way for truly green systems that do not adversely impact the environment.

C. Green Internet Technologies

The Internet, which has impacted the way we communicate and share information, is a global system of interconnected computer networks. Recently, cloud computing has provided high-performance computing resources and high-capacity storage to the end users of the Internet. Cloud can offer significant financial benefits, in that end users share a large, centrally managed pool of storage and computing resources, rather than owning and managing their own systems [37]. Cloud computing offers access to the computing resources by treating resources as services, i.e., Infrastructure as a Service, Platform as a Service, and Software as a Service, and providing them elastically based on user demands [38]. The cloud service providers invest in infrastructure and management systems to charge end users based on their time and usage of the service. The data centers hosting cloud applications consume huge amounts of energy resulting in high operational costs and large CO2 footprints [39]. Many computing services are moving to cloud computing because it provides convenient access to many resources. Ultimately, the cloud must be scaled up to support new demands and to maintain service quality. The growth results in the deployment of more resources and increased power consumption, which leads to more environmental issues and CO2 emissions. Therefore, efficient use of resources in the cloud is necessary to reduce energy consumption. The use of devices that consumes less energy, virtualization, and self-optimized software applications must be adopted to reduce energy consumption. Thus, the objective of green cloud is not

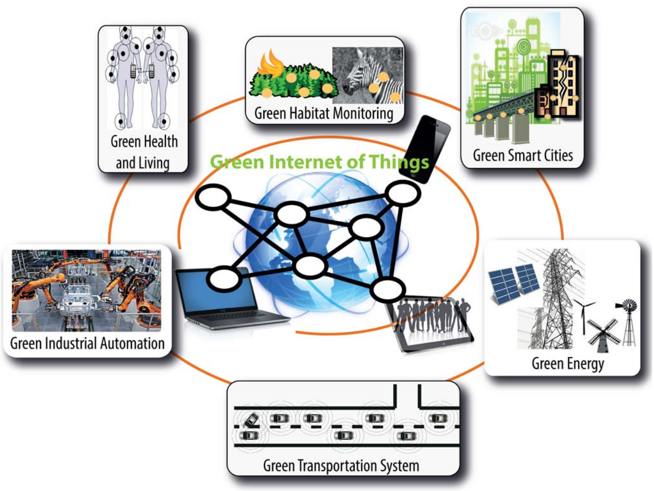

Fig. 4. Green IoT applications (adapted from [8]).

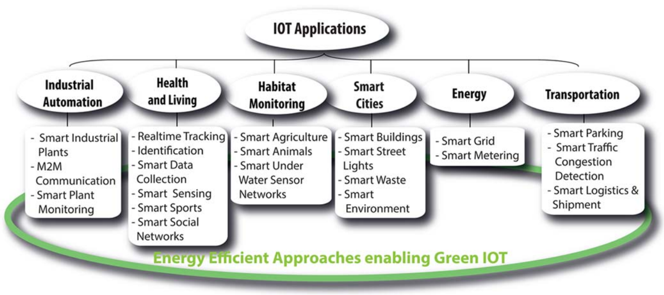

Fig. 5. Green IoT scenarios.

only to provide efficient use of resources and the computing infrastructure but to reduce carbon emissions by minimizing energy consumption. For green cloud computing, the two main categories of solutions are hardware and software that reduce energy consumption. Hardware solutions try to design and manufacture devices that consume less energy without losing the quality of their performance [40]. On the other hand, the software solutions provide efficient software designs that consume less energy by minimum utilization of the resources.

IV. IoT Applications

Potential IoT applications are numerous and diverse, covering practically all areas of everyday life. The 2012 EU IoT Strategic Research Agenda [8] identified the most attractive IoT scenarios by conducting a survey. Based on 270 responses from 31 countries, smart home, smart city, transportation, and health care were identified as promising IoT applications. Recently, Libelium has released the document "50 Sensor Applications for a Smarter World. Get Inspired!" [41], which covers the most relevant WSN and IoT applications. Accordingly, we classify these applications into six major categories based on their impact on the environment: industrial automation, health and living, habitat monitoring, smart cities, energy, and transportation system (see Fig. 4). Fig. 5 further sub-classifies each IoT application into relevant scenarios. Here, our emphasis is on exploring the IoT applications and focus on factors that can be exploited to achieve Green IoT (see Table II).

A. Industrial Automation

The United Kingdom industrial sector uses around 36 million tons of oil each year and spends over \$16 billion to do so, which constitutes over one-third of the total inland energy consumption [42]. The resultant CO2 emissions contribute to global warming and urges for a green industry. The emergence of IoT in the industrial sector leads to various applications that have helped to reduce the CO2 emissions and have provided a path for green industrial automation.

1) Smart Industrial Plants and Machine to Machine Communications: Smart environments help to improve the automation of industrial plants by using RFID tags associated with the production items. As soon as the item reaches the processing unit, the RFID reader reads the tag and generates the appropriate event. The machine/robot receives notification of the event and picks up the production item for further processing. This leads to an M2M scenario, in which the RFID reader directly communicates with the robot without any human intervention. Simultaneously, a WSN can monitor a machine's vibrations to assess its health and can trigger an event if the vibrations increase beyond a threshold value. Once such an emergency event occurs, related machines and processes react accordingly. Upon receiving the emergency shutdown event, the robot immediately stops its operation. The plant manager can maintain a global view of all the elements while also monitoring the production progress, device status, and the possible side effects of a production line delay [43]. This lowers energy costs by providing in-time event reports and ensuring that different machines will not run unnecessarily. This scenario presents a snapshot of potential energy savings; the overall impact can be much higher as a result of energy evaluation and planning conducted via WSNs [44] and by using appropriate software [45]. Furthermore, the increasing attention given to green M2M communications should further reduce the energy M2M subsystems utilize.

2) Smart Plant Monitoring: In recent years, energy efficiency has come to the forefront of corporate agendas across industries. Emerging technologies can efficiently monitor various parameters, such as temperature, air pollution, machine faults, etc., of an industrial plant [46], [47] to improve energy efficiency. In order to monitor an industrial plant, designers must first develop an energy profile for real-time energy consumption and compare it with a set of benchmarks. This involves capturing energy data related to the processes using IoT technologies. This will also help in identifying quickly the greatest energy consumers to determine how well they are doing. Determining the overall energy performance of a plant is necessary for making comparisons between current energy use and a consumption target that reflects current operations. Only then is it possible to conduct an analysis to determine the cause of deviations from the target and to take appropriate remedial actions. IoT-based approaches help to map the energy consumption better and provide green solutions.

B. Health and Living

The healthcare sector has benefited substantially from IoT technologies. Currently, efforts attempt to provide energy efficient solutions to help patients by supporting green hospitals and green equipment that require ultralow or no energy sources. Next, we will discuss the energy efficient approaches for major IoT healthcare applications.

TABLE II
COMPARISON OF IoT APPLICATIONS

Application Domains	Devices	Data Storage	# Things	Energy	Internet Connectivity	Time to Deploy	Mobile application	Achieving Greenness
Industrial Automation								
Smart Industrial Plants	RFID/WSN	proprietary central database	Large	Battery	Wifi Backbone	Medium	No	cloud, harvesting
M2M	RFID/WSN	database	Large	Battery	Wifi 3G/4G Backbone	Low	Yes	harvesting
Smart Plant Monitoring	WSN	database	Medium	Battery Harvested	Wifi Backbone	Low	No	cloud
Health and Living								
Tracking and Identification	RFID/WSN RTLMS	database	Medium	Battery	Wifi Backbone	Low	No	cloud, harvesting, mobile app.
Smart Data Collection	WSN	distributed	Large	Battery	-	Low	No	energy efficient approaches
Smart Sensing	WSN	proprietary central database	Large	Battery	Wifi Backbone	Low	Yes	cloud, information inferring
Smart Sports	WSN	database	Medium	Battery Harvested	Wifi 3G/4G	Low	Yes	cloud
Smart Social Networks	Handheld	cloud	Large	Grid	Wifi Backbone	Low-Medium	Yes	–
Habitat Monitoring								
Smart Agriculture	WSN	database	Medium - Large	Battery Harvested	3G/4G Satellite	Medium	Yes	cloud
Smart Animals	RFID/WSN	database	Small - Medium	Battery	3G/4G Satellite	Medium-Large	No	harvesting
Smart UWSN	WSN	database	Medium	Battery	Satellite Microwave	Medium-Large	No	harvesting
Smart Cities								
Smart Buildings	RFID/WSN	database	Small	Battery	Wifi Backbone	Medium-Large	Yes	cloud, harvesting
Smart Street Light	WSN	database	Small - Medium	Battery Harvested	Wifi 3G/4G	Low-Medium	No	mobile app.
Smart Waste	RFID/WSN	database	Medium	Battery	Wifi 3G/4G	Low-Medium	No	harvesting
Smart Environment	WSN	database	Medium - Large	Battery Harvested	Wifi 3G/4G Satellite	Medium-Large	No	cloud, mobile app.
Energy								
Smart Grid	WSN	proprietary central database	Large	Grid	3G/4G Backbone	Large	No	cloud
Smart Metering	WSN	database	Medium - Large	Battery Grid	3G/4G Backbone	Medium	Yes	–
Transportation								
Smart Parking	WSN	database	Medium	Battery	Wifi 3G/4G	Low-Medium	Yes	harvesting
Smart Traffic Congestion	WSN/VANET	database	Medium - Large	Battery	3G/4G Satellite	Medium-Large	Yes	cloud
Smart Logistics	RFID/WSN	database	Large	Battery Harvested	3G/4G Satellite	Medium-Large	No	cloud

1) Real-Time Tracking and Identification: This application aims to track and monitor patients and medical equipment. For example, monitoring patient flow can improve workflow in hospitals. In relation to assets, tracking assists with maintenance, availability, monitoring of use, and materials tracking to prevent left-ins during surgery. Energy efficiency can be achieved by having efficient tracking methods, such as collaborative cluster heads, which can be used in place of sensors for tracking [48], efficient RFID-based tracking [49], prediction techniques [50], etc. These technologies can support patient identification to reduce dangerous patient incidents (such as wrong drug, dose, etc.), electronic health records (in- and out-patient), and infant identification (to prevent mismatching).

2) Smart Data Collection: Smart data collection and transfer in the healthcare sector mainly support reduced processing time, automated hospital admission processing, and automated care and procedure auditing. This function also helps to integrate RFID technology with other health information and clinical application technologies within a facility. The data can be collected in an energy efficient manner and stored on clouds for further processing [51]. Using smart data collection methods also ensures patient privacy preservation [52].

3) Smart Sensing: Sensor devices provide patient conditions for diagnosis and real-time health indicators. Sensors can be applied both during in- and out-patient care, and hospitals can deploy heterogeneous wireless access-based remote patient monitoring systems to reach the patient everywhere [53]. In an effort to provide energy efficiency, developers are turning to compressive sensing solutions [54]–[56] where the signal is sampled at a sub Nyquist rate.

4) Smart Sports: There are many opportunities for IoT applications in the sports domain. Users are interested in knowing real-time statistics in the game, such as how fast a player shot a goal. Such information is also very useful for coaches planning for future games accordingly. Furthermore, these applications can easily monitor the players' health. Since players are generally physically active, designers can exploit energy harvesting schemes to take advantage of the physical activity of the players (movement, thermal, etc.) to achieve energy efficiency in these applications [57], [58].

5) Smart Social Networks: Living and interaction styles have changed a lot in recent years. Social networks enable the user to interact with other people to maintain and build social relationships. Indeed, events such as moving from/to our house/office, traveling, meeting common friends may automatically trigger an update to a status for a person's friends [59]. For energy awareness among users, social media can play a vital role and can indirectly contribute to a greener world.

C. Habitat Monitoring

The conservation of habitats is important in sustaining regional, national, and global environmental, economic, and social systems. Habitat monitoring is used to identify spatial and temporal changes, physical changes in the environment, organism changes, and changes caused by human actions or natural events. Next, we review four main applications: agriculture, forests, animals, and underwater sensor networks.

1) Smart Agriculture: One of the most ancient professions of mankind is agriculture. For agricultural processes, modern tools and technology are needed to improve the production and quality of crops [60], [61]. Smart agriculture involves applying the amount of inputs (water, pesticides, and fertilizer), completing pre- and postharvest operations, and monitoring environmental impacts. Various efficient approaches, such as irrigation system [62], [63], smart underground sensors [64], and smart insect detection [65] have been designed to perform tasks for smart agriculture. Similar approaches can be applied to forest monitoring [66], [67] where the major focus is forest fire monitoring [28], [68], [69] since fires often result in significant damage to the environment.

2) Smart Animals: The farming industry is an important sector for any country's economy. In recent history, many animals have been slaughtered and incinerated to stop the spread of diseases such as bovine spongiform encephalopathy, foot and mouth disease, and bird flu. These diseases not only disrupt the economy of a country but also create environmental problems. Properly monitoring animals' behavior and correlating it with environmental information to determine optimal management intervention strategies can reduce the environmental impact of animals [70]–[72].

3) Smart Underwater Sensor Networks: Underwater sensor network (UWSN) can be applied in oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, assisted navigation, and tactical surveillance applications. UWSN consist of a variable number of sensors that are deployed underwater to perform collaborative tasks using acoustic signals [73], [74].

D. Smart Cities

Due to better health facilities, greater access to education and a large job market people tend to move to cities. Cities represent a complex, dynamic environment that can cater for a large number of citizens and businesses. The concept of the "smart city" has recently been introduced as a strategic venture to facilitate urban population growth and to highlight the importance of IoT for managing it [75]. Next, we discuss the important applications in this class.

1) Smart Buildings: Efforts to make buildings smarter focus on reducing energy consumption by redefining building operations such as air conditioning, heating, and lighting. Building automation can reduce the annual operating costs of buildings and lead to a green environment [76], [77].

2) Smart Street Lights: In general, the streetlight monitoring involves having control at the level of the streetlight transformer station. Conventional street lighting systems remain turned on until morning (and sometimes even later) and humans are required to turn off the streetlights. In some areas, where a few people are on the streets, the streetlights remain on for most of the night without purpose. The consequence is that a large amount of power is wasted. By implementing energy efficient WSNs monitoring systems, the majority of these problems can be solved [78], [79], resulting in significant energy savings.

3) Smart Waste: The high population density of urban areas makes solid waste management a significant problem. To reduce the environmental impact of waste dumping, many municipal and corporate bodies are involved in the development of efficient waste management systems [80]. Embedding RFID readers on waste bins can make them intelligent. When trash (with an RFID tag) is deposited into the bin, the bin can identify the type of trash to facilitate the recycling process [81]. Furthermore, the waste bins can communicate with each other (by routing information across them) to better manipulate the waste [82]. Such smart practices help promote a healthy environment.

4) Smart Environment: Increasing number of vehicles, urbanization and many industrial activities have increased air pollution considerably in the last few decades. Air pollution monitoring is considered to be very complex as well as important task. Traditionally, data loggers were used to collect data periodically with bulky equipment that was time consuming and quite expensive to operate. The use of IoT technology can make air pollution monitoring less complex and help in better understanding the environment [46].

E. Energy

1) Smart Grid: Public awareness about the changing paradigm of energy supplies, consumption, and infrastructure is increasing. Rather than being based on fossil resources or nuclear energy, the future energy supply needs to be based largely on various renewable resources. The future electrical grid must be flexible enough to react to power fluctuations by controlling energy sources and the consumption by the consumers. Such grid will be based on networked smart devices (appliances, generation equipment, infrastructure, and consumer products) based on IoT concepts.

2) Smart Metering: A smart meter periodically records the consumption of electric energy and transmits that information to the utility company for monitoring and billing purposes [83]. Smart meters enable two-way communication between the smart meter and the utility company [84]. In contrast, traditional meters only measure total consumption, and provide no information regarding how the energy was consumed. On the other hand, smart meters provide site-specific information that can offer a number of potential benefits to householders. These include a) an end to estimated bills; and b) a tool to better manage their energy use that can help to reduce their energy bills and carbon emissions [85].

F. Transportation

Recently, cars, trains, buses, bicycles, and roads have been equipped with tags, sensors, actuators, and the necessary processing power to send important information to traffic control sites. Such advanced transportation systems help to route traffic better, provide tourists with appropriate transportation information, and monitor the status of transported goods. In the following, we review the main applications in the smart transportation category.

1) Smart Parking: The increasing availability of vehicles in recent years has created a problem of finding vacant places to park the vehicles, particularly in major cities. This situation contributes to air pollution, fuel waste, and motorist frustration. This problem can be solved by introducing a Smart Parking Systems, which is an efficient and cost-effective approach based on IoT technologies [86], [87].

2) Smart Traffic Congestion Detection: With the growing worldwide population, traffic problems, such as traffic congestion, etc., are increasing daily. By using the technology of vehicular ad hoc networks (VANETs), it is possible to avoid traffic congestion allowing vehicles to communicate with each other and to share road information to better understand road conditions. This will reduce carbon emissions and help to build a green environment [88], [89].

3) Smart Logistics/Shipment: Information collected through RFID, NFC, and sensors can enable real-time monitoring of the supply chain system. These technologies can also gather product-related information in real time to help enterprises to respond to changing markets in the shortest possible time. Generally, to realize customer requirement a typical enterprise requires around 120 days. In contrast, enterprises using advanced technologies (such as Wal-mart and Metro) only need few days to fulfill customer demands [90], [91]. Furthermore, fruits, meat, and dairy products travel thousands of miles from the production site to consumption sites and require constant monitoring to ensure quality standards. IoT enabled technologies offer great potential for improving the efficiency of the food supply chain and for helping to limit the carbon footprint [92], [93].

G. Lessons Learned

Referring to Table II, we present in the following some of the lessons learned from current IoT applications that will be useful in achieving a green IoT environment in the future.

Simplicity. The ultimate acceptance and adoption of many IoT devices will depend on their ease of use whether directly by end users or in other user appliances. Consequently, the simplicity of installation and ease of use by end users are important design considerations that must be taken into account for IoT devices and applications.

Sensing or inferring. The continuous sensing by sensors often cause them to drain their energy rapidly. To save energy, various sleeping techniques have been proposed in the past. In many cases, inferring from past data can be adequate [94] and is an area that can lead to significant energy savings for sensor devices and worth investigating in the future.

Data and context-awareness. Only collecting huge amounts of data without any context will not be of much use later on and will consume a lot of resources unnecessarily. One of the most daunting challenges faced by IoT is to preserve the context of the data generated so that future processing of such data leads to more meaningful results. Future IoT devices need to not only collect data but also preserve the contexts where the data is collected.

Interference-free connectivity. The increasing number of IoT devices that are being deployed is going to lead to increased competition for the available spectrum as well as increased interferences [95]. Future IoT devices need to be designed so that they can still operate in environments subjected to interferences and need to be able to mitigate interferences from other IoT devices effectively with minimal impact on their resource consumption.

Impact of Mobile Applications. In the past, extensions to devices were mostly hardware based and not very flexible. Today, with technological advances of networks, faster processors, cheaper memory, extending the functionality of a device such as an IoT device is often possible by downloading a mobile application to the device. As a result, it is easier and quicker to connect to new products emerging on the market. This means that it would be desirable if future IoT devices support the flexibility and user-friendliness provided by various types of mobile applications.

V. Green IoT-Related Projects and Standardization

In recent years, a growing number of green projects have been funded to facilitate the research, experimentation, deployment, and evaluation of green techniques for IoT. Here, we review research projects and standardization efforts concerning green IoT initiatives.

Governments across the world have put forth initiatives to force corporations to reduce carbon emissions, become more energy efficient, and use greener techniques. The EU FP7 program has supported several long-term research projects. Among them, project EARTH [96] investigates the energy efficiency of wireless communication systems. It focuses on the theoretical and practical energy efficiency limitations of current networks to develop a new generation of energy efficient equipment, deployment strategies, and network management solutions to ensure quality of service (QoS). The EU FP7 includes another project known as Toward Real Energy-efficient Network Design (TREND) [97] focusing on energy-efficient networking. The TREND project collects power consumption data, assesses the energy-saving potential of technologies, protocols, architectures, and experiments with new approaches. The EU FP7 also includes training programs to spread green network awareness, i.e., GreenNet [98].

The IEEE Communication Society has also established a Technical Subcommittee on Green Communications and Computing (TSCGCC) [99]. TSCGCC works to develop and standardize energy-efficient communications and computing. It also provides opportunities to interact and exchange technical ideas, to identify R&D challenges, and to collaborate on solutions for the development of energy-sustainable, resource-saving, and environmentally friendly green communications and computing technologies.

Another consortium, GreenTouch [100], consists of approximately 30 leading ICT companies and research institutes that have come together to transform communications and data networks. GreenTouch places emphasis on reducing the CO2 footprint of ICT devices and networks.

Cool silicon [101] focuses on building the technological basis necessary to support a massive increase in energy efficiency in the ICT sector. Cool silicon targets high energy efficiency for micro- and nanotechnologies and green communication systems and seeks to develop energy-efficient sensors.

TABLE III
STANDARDIZATION ACTIVITIES FOR GREEN IoT

Standard/Projects	Status	Region	Organizer	Green Perspective
Earth [96]	Completed (2012)	Europe	EU FP7 IP	energy efficient wireless communication
TREND [97]	Ongoing	Europe	EU FP7 IP	energy-efficient networking
Green Net [98]	Ongoing	Europe	EU FP7 IP	training of green communications
TSCGCC [99]	Advance	Global	IEEE	energy efficient computing standardization
GreenTouch [100]	Advance	Global	GreenTouch Consortium	reduction of CO2 footprint of ICT
Cool Silicon [101]	Ongoing	Europe (Germany)	Silicon Saxony Management	energy efficiency in the ICT
Celtic-Plus [102]	Ongoing	Europe	ICT industry partners	smart connected world
GREEN-T [103]	Ongoing	Europe	CELTIC-PLUS	energy-efficiency in heterogeneous wireless networks
Green IT [104]	Completed	Japan	METI & JEITA	energy efficiency of data centers, networks and displays
Go Energi [105]	Ongoing	Europe (Denmark)	Danish Energy Saving Trust	energy efficiency in households, commercial and industrial sector
Green Radio [106]	Ongoing	UK	MVCE	green architectures
Green Grid [107]	Ongoing	Global	Global ICT Companies	energy efficiency of data centers
6LoWPAN [108]	Ongoing	Global	IETF	IPv6 for low end devices
ROLL [109]	Ongoing	Global	IETF	routing for low end devices
EPCglobal [110]	Advance	Europe	ETSI, CEN, ISO	RFID technology
M2M [114]	Ongoing	Global	ITU-T/ETSI	M2M standardization
NFC [115]	Advance	Global	ISO	low range communication protocols
Zigbee [116]	Advance	Global	ZigBee Alliance	ZigBee standardization

Celtic-Plus [102] is an industry-driven EU research initiative that supports various projects. Among them, the GREEN-T [103] mainly focus on new approaches to optimize energy efficiency in heterogeneous wireless networks. Similarly, the green IT [104], an initiative of the Japan, targets the energy efficiency techniques of data centers, networks and displays. The Danish Energy Saving Trust (Go' Energi) [105] promotes energy efficiency in households, the public sector, and the commercial and industrial sectors for all forms of energy use. In the United Kingdom, Mobile VCE targets the parallel evolution of green architectures and techniques in the Green Radio project [106]. The green Grid [107], a global consortium, specifically targets the energy efficiency of the data centers.

Full deployment of IoT relies on several ongoing contributions from various projects and companies. To make IPv6 suitable for low-end devices, such as sensor nodes and RFID, the Internet Engineering Task Force (IETF) is working on two major initiatives: 6LoWPAN [108] and Routing Over Low power and Lossy networks (ROLL) [109]. EPCglobal [110], the European Telecommunications Standards Institute (ETSI) [111], European Committee for Standardization (CEN) [112], and the International Standard Organization (ISO) [113] are making major contributions to standardize RFID technology. ETSI has also launched the M2M Technical Committee [114] to standardize activities related to IoT for M2M and WSN.

Table III summarizes the projects and standardization activities currently underway to enable Green IoT.

VI. CHALLENGES AND OPPORTUNITIES FOR GREEN IoT

Green technologies will play an important role in enabling the energy-efficient IoT. There are many challenging issues that need to be addressed. Here, we summarize them and highlight the key issues that need further consideration.

A. *Green IoT Architectures*

For IoT, a standard architecture, such as the ISO OSI model or the TCP/IP model, is needed to enable communication across various applications and heterogeneous networks that have a wide variety of devices. Moreover, it is important to understand how to integrate energy efficiency across the whole architecture. Both the devices and the protocols used to communicate should be energy efficient. Similarly, the applications should be energy efficient to ensure that their overall impact on the environment is minimal. As is evident from Section V, academia and the industry sector must work together to promote and standardize the green IoT paradigm making the exploration of green IoT architectures a priority.

B. *Green Infrastructure*

Providing energy efficient infrastructure for IoT can be achieved through a clean-slate redesign approach. However, due to the complexity of deploying a radically new infrastructure (or even adapting an existing infrastructure over time), this area of research is less focused and requires further attention. Accordingly, many interesting issues such as quantifying the potential benefits of designing new energy-efficient infrastructure while efficiently exploiting the current infrastructure, remain open at both the architectural and operational levels.

C. *Green Spectrum Management*

Currently, users are confined to the limited RF spectrum, which is quite congested and difficult to use optimally. The cognitive radio approach [117] allows devices to sense the various RF channels and to tune both transmission and reception dynamically to avoid interference with concurrent users. The cognitive radio approach brings many benefits to green mobile services [118]. Although the cognitive radio efficiently manages the spectrum, it relies on continuous monitoring of the RF spectrum, which may cause it to consume more energy. In order to explore the full potential of cognitive radios more analysis in this area is needed to identify tradeoffs between efficient dynamic spectrum management and efficient spectrum sensing. Current efforts are limited to simulation studies, thereby providing an opportunity to develop and experiment with the cognitive radio hardware.

D. Green Communication

The energy-efficient communication faces many challenges such as providing a continuous energy supply to objects in loop and supporting energy-efficient communication protocols that enable peers to communicate in a reliable manner, etc. Furthermore, cyberphysical systems (CPS) [119] are evolving due to the use of sensors, M2M, and energy harvesting mechanisms to monitor and control physical environments. Since CPS and M2M directly interfere with the physical world, the balance among performance, safety, and energy efficiency of CPSs and M2M should be a high priority for investigators and developers. Future research that focuses on integrating M2M for ubiquitous services will be critical for developments in this area. Alongside energy-efficient mechanisms for IoT, several attempts are underway to discover new energy sources that can provide a new dimension to green IoT [120]. Efficient adoption of new energy sources, such as wind, solar, thermal, and vibration to assist the current green IoT appear promising.

Furthermore, scalability will be a major concern for green IoT applications. Tethering and multihopping can improve the scalability [121], [122]. Tethering enables groups of users to communicate directly with a host in an adhoc manner, whereas the host is connected to the Internet. Multihopping is a common technique to save energy and overcome the scalability issue [123]–[125]. Another potential solution to address the scalability problem involves the efficient exploitation of the mobility of users and objects in the network [126], [127]. This opens an opportunity to find a tradeoff between energy efficiency and using mobility to address the scalability problem.

D. Green Security and QoS Provisioning

Security and privacy are major concerns for IoT deployment. Implementing of security algorithms requires a substantial amount of processing from devices. The potential of energy efficient, secure mechanisms, which are still in their infancy, should encourage more research and development in this area [128]. Since IoT involves both resource-constrained devices, such as RFID and sensor nodes, and high-end data servers, it is important to find and exploit tradeoffs to provide security among heterogeneous devices in the green IoT paradigm. Generally, security is often viewed as an add-on to the system. But, in the case of green IoT, security must be given high priority and should be considered early during the design phase. Along with the security, we need to investigate appropriate mechanisms that consider both energy consumption and the required QoS. Several critical issues (such as the heterogeneity of devices and applications) to enable green QoS require further investigation.

VII. Conclusion

In this paper, we have surveyed the green perspective of the IoT. We have discussed recent efforts in the green IoT area and we have identified potential areas where the focus should be in the future for green IoT. We identify the list of applications of IoT where the energy can be saved to have green environment. This paper also focuses on the key enablers of green IoT and showed how they take advantage of different techniques to enable energy efficiency. The need of standard architectures is highlighted to have smooth interaction across different domains of green IoT, particularly heterogenous commination, sensor-cloud integration, proper service management, and harsh physical environments. There are many international efforts to promote and adapt the green environment. Accordingly, we have surveyed the current projects and standardization efforts and highlight their future standpoints. We believe that having industry interest in the area of green IoT makes its future brighter and having the academia fully involved will make the vision of green IoT realized.

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