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Green Internet of Things for Smart World

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ABSTRACT Smart world is envisioned as an era in which objects (e.g., watches, mobile phones, computers, cars, buses, and trains) can automatically and intelligently serve people in a collaborative manner. Paving the way for smart world, Internet of Things (IoT) connects everything in the smart world. Motivated by achieving a sustainable smart world, this paper discusses various technologies and issues regarding green IoT, which further reduces the energy consumption of IoT. Particularly, an overview regarding IoT and green IoT is performed first. Then, the hot green information and communications technologies (ICTs) (e.g., green radio-frequency identification, green wireless sensor network, green cloud computing, green machine to machine, and green data center) enabling green IoT are studied, and general green ICT principles are summarized. Furthermore, the latest developments and future vision about sensor cloud, which is a novel paradigm in green IoT, are reviewed and introduced, respectively. Finally, future research directions and open problems about green IoT are presented. Our work targets to be an enlightening and latest guidance for research with respect to green IoT and smart world.

INDEX TERMS Smart world, Internet of Things, green, radio-frequency identification, wireless sensor network, cloud computing, machine to machine, data center, sensor-cloud.

I. INTRODUCTION

A. SMART WORLD

With the rapid development of science and technology, the world is becoming ‘‘smart’’. Living in such a smart world [1], people will be automatically and collaboratively served by the smart devices (e.g., watches, mobile phones, computers), smart transportation (e.g., cars, buses, trains), smart environments (e.g., homes, offices, factories), etc. For example, using a global positioning system (GPS), a person's location can be continuously uploaded to a server that instantly returns the best route to the person's travel destination, keeping the person from getting stuck in traffic. In addition, the audio sensor inside a person's mobile phone can automatically detect and send any abnormality in a person's voice to a server that compares the abnormality with a series of voiceprints to determine whether the person has some illness. Eventually, all aspects regarding people's cyber, physical, social and mental world will be interconnected and intelligent in smart world. As the next important stage in human history, smart world is receiving numerous attention from academia, industry, government, etc.

B. RESEARCH MOTIVATION

Our world is consisted of various ‘‘things’’. As one of the enablers of smart world, internet of things (IoT) [2]–[7] targets to connect various objects (e.g., mobile phones, computers, cars, appliances) with unique addresses, to enable them interacting with each other and with the world. Further, green IoT targets at a sustainable smart world, by reducing the energy consumption of IoT.

In this paper, aiming at fulfilling a sustainable smart world, we position our focus on green IoT and study various technologies towards green IoT. Specifically, an overview about IoT and green IoT is performed first. Then the hot green information and communications technologies (ICT) (e.g., green radio-frequency identification (RFID) [8], green wireless sensor network (WSN) [9], green cloud computing (CC) [10], green machine to machine (M2M) [11], green data center (DC) [12]) enabling green IoT are discussed, followed with the summary of general green ICT principles. With that, towards green IoT, we review the latest developments in sensor-cloud [13], [14] which is a novel paradigm in green IoT, and further envision the future sensor-cloud. Eventually, future research directions and open problems about green IoT are shown. To the best of our knowledge, this work is the first that discusses the realization of smart world from the view of green IoT. We hope this work could be an enlightening and latest guidance for research concerning green IoT and smart world.

C. RESEARCH CONTRIBUTION

The main contributions of this paper are shown as follows.

- Enabling green IoT, this paper discusses the hot green ICT (e.g., green RIFD, green WSN, green CC, green M2M and green DC) and further summarizes the general green ICT principles.
- Towards green IoT, this paper reviews the recent developments about sensor-cloud and envisions the future sensor-cloud. In addition, this paper presents the future research directions and open problems regarding green IoT.

D. ORGANIZATION

For the rest part of this paper, Section II briefly describes IoT and green IoT. Section III discusses and summarizes the green ICT enabling green IoT. The latest research about sensor-cloud and future sensor-cloud towards green IoT are shown in Section IV. Section V presents the future research directions and open problems with respect to green IoT. Section VI concludes this paper.

II. OVERVIEW OF IoT AND GREEN IoT

A. IoT

1) DEFINITION

There are various deifications regarding IoT [2]–[7]. We list two examples by ITU-T (International Telecommunication Union (ITU) Telecommunication Standardization Sector) and IERC (IoT European Research Cluster), respectively. *Definition of ITU-T*: ‘‘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.’’ *Definition of IERC*: ‘‘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.’’

In short, as shown in Fig. 1, the basic idea of *IoT* is that everything (e.g., from small rooms to large buildings, from everyday appliances to sophisticated embedded systems, from man-made artifacts to natural objects) around us could be connected, sense and cooperatively communicate over the Internet.

2) ELEMENTS

The elements in IoT [6] are presented in Fig. 2. Specifically, there are six elements in IoT, i.e., *identification*, *sensing*, *communication technologies*, *computation*, *services* and *semantic*.

Identification plays a crucial role in naming and matching services with their demand. Examples of identification methods used for the IoT are electronic product codes (EPC), ubiquitous codes (uCode), etc. *Sensing* is for collecting various data from related objects and sending it to a database, data warehouse, data center, etc. The gathered data is further analyzed to perform specific actions based on required services. The sensors can be humidity sensors, temperature sensors, wearable sensing devices, mobile phones, etc. *Communication technologies* connect heterogeneous objects together to offer specific services. The communication protocols available for the IoT are: Wi-Fi, Bluetooth, IEEE 802.15.4, Z-wave, LTE-Advanced, Near Field Communication (NFC), ultra-wide bandwidth (UWB), etc.

About *computation*, the hardware processing units (e.g., microcontrollers, microprocessors, system on chips (SoCs), field programmable gate arrays (FPGAs)) and software applications perform this task. Many hardware platforms (e.g., Arduino, UDOO, FriendlyARM, Intel Galileo, Raspberry PI, Gadgeteer) are developed and various software platforms (e.g., TinyOS, LiteOS, Riot OS) are utilized. Cloud platform is a particular important computational part of IoT, since it is very powerful in processing various data in real-time and extracting all kinds of valuable information from the gathered data. The *services* in IoT can be categorized into four classes: identity-related services, information aggregation services, collaborative-aware services and ubiquitous services. Identity-related services lay the foundation for other types of services, since every application mapping real world objects into the virtual world needs to identify the objects first. Information aggregation services, gather and summarize the raw information which need to be processed and reported. The obtained data are further utilized by the collaborative-aware services to make decisions and react accordingly. Ubiquitous services, are for offering the collaborative-aware services to anyone on demand, anytime and anywhere. *Semantic* means the ability to extract knowledge intelligently so as to provide the required services. This process

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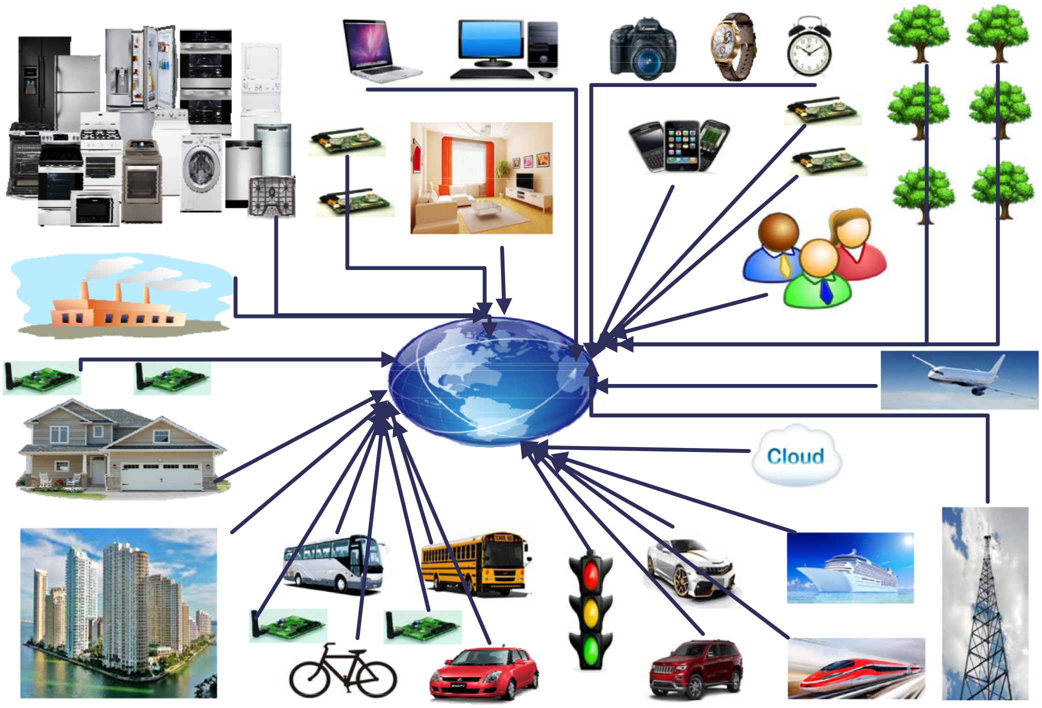

FIGURE 1. An example of IoT.

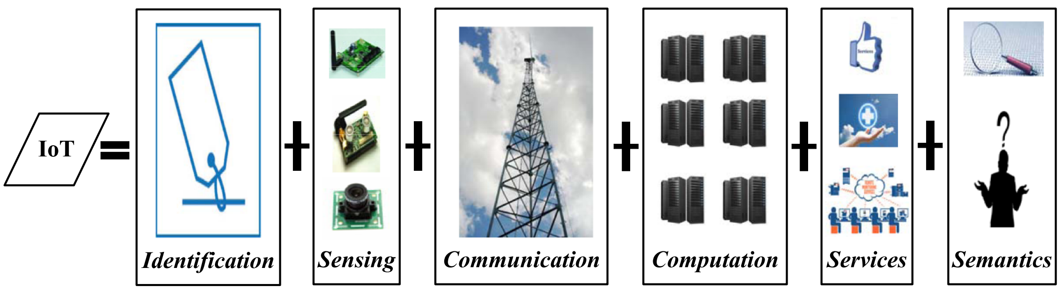

FIGURE 2. Elements in IoT.

usually includes: discovering resources, utilizing resources, modeling information, recognizing and analyzing data. The commonly used semantic technologies are: resource description framework (RDF), web ontology language (OWL), efficient XML interchange (EXI), etc.

B. GREEN IoT

Enabling the smart world, IoT is included by the NIC (National Intelligence Council) of U.S. among six ''Innovative Civil Technologies'' that will impact U.S. power grids. It is foreseen by NIC that ''by 2025, internet nodes may reside in everyday things, i.e., food packages, furniture, paper documents, and more.'' However, to enable a sustainable smart world, the IoT should be characterized by energy efficiency [15]. Particularly, since all devices in the smart world are supposed to be equipped with additional sensory and communication add-ons so that they can sense the world and communicate with each other, they will require more energy. In addition, driven by the growing interest and adoption from various organizations, the energy demand will further greatly increase.

All these make green IoT which focuses on reducing the energy consumption of IoT a necessity, in terms of fulfilling the smart world with sustainability. Considering the energy efficiency as the key during the design and development of IoT, *green IoT* can be defined as follows [7].

''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.''

C. APPLICATION

With respect to IoT and green IoT, there are a lot of applications [2]–[7]. We list some application scenarios as follows.

Smart Home: Personal life-style at home is enhanced, by making it more convenient and easier to monitor and operate home appliances and systems (e.g., microwave, oven, air conditioner, heating systems, etc.) remotely. For instance, based on the weather forecast information, a smart home can automatically lower the blinds of windows and close the windows.

Industrial Automation: With a minimal human involvement, robotic devices are computerized to finish manufacturing tasks. The machines' operations, functionalities, and productivity rates are automatically controlled and monitored. For example, if there is a sudden issue about a machine, the system will immediately deliver a maintenance request to the maintenance department for handling the problem. In addition, the productivity is improved, by analyzing production data, timing and causes of production issues.

Smart Healthcare: Performance of healthcare applications is improved, by embedding sensors and actuators in patients and their medicine for monitoring and tracking patients. For instance, by gathering and analyzing patients' body data with sensors and further delivering analyzed data to a processing center, the clinical care could monitor physiological statuses of patients in real-time and make suitable actions when necessary.

Smart Grid: Power suppliers are assisted to control and manage resources so that power can be offered proportionally to the population growth. Therefore, the energy consumption of houses and buildings could be enhanced. For example, the meters of buildings could be connected to the network of energy providers. Then the energy providers could enhance their services, by collecting, analyzing, controlling, monitoring, and managing energy consumption. Meanwhile, the potential failures could be reduced.

Smart City: Quality of life in the city is ameliorated, by making it more convenient and easier for the residents to obtain information of interest. For instance, according to people's needs, various interconnected systems intelligently offer the desirable services (e.g., transportation, utilities, health, etc.) to people.

III. ICT ENABLING GREEN IoT

In this section, we first present an overview of ICT. Then five hot green ICT (i.e., green RFID, green WSN, green M2M, green CC and green DC) enabling green IoT are discussed, followed with the general principles of green ICT.

A. OVERVIEW OF ICT

ICT is an umbrella term that relates to any facility, technology, application (e.g., radio, television, cellular phones, computers, machines, networks, hardware, software, middleware, storage, satellite systems, videoconferencing, distance learning) regarding information and communication, enabling users to access, store, transmit, and manipulate a variety of information. In this paper, we list the following ICT, regarding identification, sensing, communication and computation which are IoT elements introduced in Section II.

- *RFID (radio-frequency identification)* [16]: a small electronic device that consists of a small chip and an antenna, automatically identifying and tracking tags attached to objects.
- *WSN (wireless sensor network)* [17]: a network consisting of spatially distributed autonomous sensors that cooperatively monitor the physical or environmental conditions (e.g., temperature, sound, vibration, pressure, motion, etc.).
- *WPAN (wireless personal area network)* [18]: a low-range wireless network for interconnecting devices centered around an individual person's workspace.
- *WBAN (wireless body area network)* [19]: a wireless network consisting of wearable or portable computing devices (e.g., sensors, actuators) situated on or in the body.
- *HAN (home area network)* [20]: a type of local area networks (LANs), connecting digital devices present inside or within the close vicinity of a home.
- *NAN (neighborhood area network)* [21]: an offshoot of Wi-Fi hotspots and wireless local area networks (WLANs), enabling users to connect to the internet quickly and at very little expense.
- *M2M (machine to machine)* [22]: a technology that allows both wireless and wired devices to communicate with other devices of the same type.
- *CC (cloud computing)* [23]: a novel computing model for enabling convenient, on-demand network access to a shared pool of configurable resources (e.g., networks, servers, storage, applications, services). Integrating CC into a mobile environment, mobile cloud computing (MCC) can further offload much of the data processing and storage tasks from mobile devices (e.g., smart phones, tablets, etc.) to the cloud.
- *DC (data center)* [24]: a repository (physical or virtual) for the storage, management, and dissemination of data and information.

B. GREEN RFID

RFID includes several RFID tags and a very small subset of tag readers. Enclosed in an adhesive sticker, the RFID tag is a small microchip attached to a radio (utilized for receiving and transmitting the signal), with a unique identifier. The purpose of RFID tags is storing information regarding the objects to which they are attached. The basic process is that the information flow is triggered by RFID tag readers through transmitting a query signal, followed with the responses of nearby RFID tags. Generally, the transmission range of RFID systems is very low (i.e., a few meters). Furthermore, various bands (i.e., from low frequencies at 124-135 kHz up to ultrahigh frequencies at 860-960 MHz) are used to perform transmission. Two kinds of RFID tags (i.e., active tags and passive tags) exist. Active tags have batteries powering the signal transmissions and increasing the transmission ranges, while the passive tags are without onboard batteries and need to harvest energy from the reader signal with the principle of induction.

For green RFID [7], [8], [25]–[28], 1) Reducing the sizes of RFID tags should be considered to decrease the amount of nondegradable material used in their manufacturing (e.g., biodegradable RFID tags, printable RFID tags, paper-based RFID tags), because the tags themselves are difficult to recycle generally; 2) Energy-efficient algorithms and protocols should be used to optimize tag estimation, adjust transmission power level dynamically, avoid tag collision, avoid overhearing, etc.

C. GREEN WSN

A WSN usually consists of a certain number of sensor nodes and a base station (BS) (i.e., sink node). The sensor nodes are with low processing, limited power, and storage capacity, while the BS is very powerful. Sensor nodes equipped with multiple on-board sensors, take readings (e.g., temperature, humidity, acceleration, etc.) from the surroundings first. Then they cooperate with each other and deliver the sensory data to the BS in an ad hoc manner generally. A commonly used commercial WSN solution is based on the IEEE 802.15.4 standard, which covers the physical and medium access control (MAC) layers for low-power and low-bit-rate communications.

Regarding green WSN, the following techniques should be adopted [7], [9], [29], [30]: 1) Make sensor nodes only work when necessary, while spending the rest of their lifetime in a *sleep mode* to save energy consumption; 2) Energy depletion (e.g., wireless charging, utilizing energy harvesting mechanisms which generate power from the environment (e.g., sun, kinetic energy, vibration, temperature differentials, etc.)); 3) Radio optimization techniques (e.g., transmission power control, modulation optimization, cooperative communication, directional antennas, energy-efficient cognitive radio (CR)); 4) Data reduction mechanisms (e.g., aggregation, adaptive sampling, compression, network coding); 5) Energy-efficient routing techniques (e.g., cluster architectures, energy as a routing metric, multipath routing, relay node placement, node mobility).

D. GREEN CC

In CC, resources are treated as services, i.e., IaaS (Infrastructure as a Service), PaaS (Platform as a Service) and SaaS (Software as a Service). Based on users' demands, CC elastically offers various resources (e.g., high-performance computing resources and high-capacity storage) to users. Rather than owning and managing their own resources, users share a large and managed pool of resources, with convenient access. With growing applications moved to cloud, more resources need to be deployed and more power are consumed, resulting in more environmental issues and CO_2 emissions.

With respect to green CC, potential solutions are shown as follows [7], [10], [31]–[34]. 1) Adoption of hardware and software that decrease energy consumption. In this regard, hardware solutions should target at designing and manufacturing devices which consume less energy. Software solutions should try to offer efficient software designs consuming less energy with minimum resource utilization; 2) Power-saving virtual machine (VM) techniques (e.g., VM consolidation, VM migration, VM placement, VM allocation); 3) Various energy-efficient resource allocation mechanisms (e.g., auction-based resource allocation, gossip-based resource allocation) and related task scheduling mechanisms; 4) Effective and accurate models and evaluation approaches regarding energy-saving policies; 5) Green CC schemes based on cloud supporting technologies (e.g., networks, communications, etc.).

E. GREEN M2M

In terms of M2M communications, massive M2M nodes which intelligently gather the monitored data are deployed in M2M domain. In network domain, the wired/wireless network relays the gathered data to the BS. The BS further supports various M2M applications over network in the application domain.

Concerning green M2M, with the massive machines involved in M2M communications, it will consume a lot of energy, particularly in M2M domain. The following methods might be used to increase energy efficiency [11], [35]–[38]: 1) Intelligently adjust the transmission power (e.g., to the minimal necessary level); 2) Design efficient communication protocols (e.g., routing protocols) with the application of algorithmic and distributed computing techniques; 3) Activity scheduling, in which the objective is to switch some nodes to low-power operation (''sleeping'') mode so that only a subset of connected nodes remain active while keeping the functionality (e.g., data gathering) of the original network; 4) Joint energy-saving mechanisms (e.g., with overload protection and resources allocation); 5) Employ energy harvesting and the advantages (e.g., spectrum sensing, spectrum management, interference mitigation, power optimization) of CR.

F. GREEN DC

The main job of DCs is to store, manage, process and disseminate various data and applications, created by users, things, systems, etc. Generally, dealing with various data and applications, DCs consume huge amounts of energy with high operational costs and large CO_2 footprints. Furthermore, with the increasing generation of huge amounts of data by various pervasive and ubiquitous things or objects (e.g., mobile phones, sensors, etc.) on the way to smart world, the energy efficiency for DCs becomes more pressing.

About green DC, possible techniques to improve energy efficiency can be achieved from the following

TABLE 1. A summary of green ICT enabling green IoT.

Scheme	Techniques
Green RFID	1) Reduce the sizes of RFID tags to decrease the amount of nondegradable material used in their manufacturing; 2) Energy-efficient algorithms and protocols for optimizing tag estimation, adjusting transmission power level dynamically, avoiding tag collision, avoiding overhearing, etc.
Green WSN	1) Make sensor nodes only work when necessary, while spending the rest of their lifetime in a sleep mode; 2) Energy depletion (e.g., wireless charging, energy harvesting mechanisms which generate power from the environment (e.g., sun, kinetic energy, vibration, temperature differentials, etc.)); 3) Radio optimization techniques (e.g., transmission power control, modulation optimization, cooperative communication, directional antennas, energy-efficient cognitive radio (CR)); 4) Data reduction mechanisms (e.g., aggregation, adaptive sampling, compression, network coding); 5) Energy-efficient routing techniques (e.g., cluster architectures, energy as a routing metric, multipath routing, relay node placement, node mobility).
Green CC	1) Adoption of hardware and software that decrease energy consumption; 2) Power-saving virtual machine (VM) techniques (e.g., VM consolidation, VM migration, VM placement, VM allocation); 3) Various energy-efficient resource allocation mechanisms (e.g., auction-based resource allocation, gossip-based resource allocation) and related task scheduling mechanisms; 4) Effective and accurate models and evaluation approaches regarding energy-saving policies; 5) Green CC schemes based on cloud supporting technologies (e.g., networks, communications, etc.).
Green M2M	1) Intelligently adjust the transmission power (e.g., to the minimal necessary level); 2) Design efficient communication protocols (e.g., routing protocols) with the application of algorithmic and distributed computing techniques; 3) Activity scheduling, in which the objective is to switch some nodes to low-power operation ("sleeping") mode; 4) Joint energy-saving mechanisms (e.g., with overload protection and resources allocation); 5) Employ energy harvesting and the advantages (e.g., spectrum sensing, spectrum management, interference mitigation, power optimization) of CR.
Green DC	1) Use renewable or green sources of energy (e.g., wind, water, solar energy, heat pumps, etc.); 2) Utilize efficient dynamic power-management technologies (e.g., Turboboost, vSphere); 3) Design more energy-efficient hardware (e.g., exploiting the advantages of DVFS (dynamic voltage and frequency scaling) techniques and VOVO (vary-on/vary-off) techniques)); 4) Design novel energy-efficient data center architectures (e.g., nano data centers) to achieve power conservation; 5) Design energy-aware routing algorithms to consolidate traffic flows to a subset of the network and power off idle devices; 6) Construct effective and accurate data center power models; 7) Draw support from communication and computing techniques (e.g., optical communication, virtual machine migration, placement optimization, etc.).
General green ICT	1) Turn off facilities that are not needed (e.g., sleep scheduling); 2) Send only data that are needed (e.g., predictive data delivery); 3) Minimize length of data path (e.g., routing schemes, network working mechanisms); 4) Minimize length of wireless data path (e.g., energy-efficient architectural designs, cooperative relaying); 5) Trade off processing for communications (e.g., data fusion, compressive sensing); 6) Advanced communication techniques (e.g., multiple-input multiple-output (MIMO), CR); 7) Renewable green power sources (e.g., oxygen, fresh water, solar energy, timber, biomass).

aspects [12], [24], [39]–[41]. 1) Use renewable or green sources of energy (e.g., wind, water, solar energy, heat pumps, etc.); 2) Utilize efficient dynamic power-management technologies (e.g., Turboboost, vSphere); 3) Design more energy-efficient hardware (e.g., exploiting the advantages of DVFS (dynamic voltage and frequency scaling) techniques and VOVO (vary-on/vary-off) techniques); 4) Design novel energy-efficient data center architectures (e.g., nano data centers) to achieve power conservation; 5) Design energy-aware routing algorithms to consolidate traffic flows to a subset of the network and power off the idle devices; 6) Construct effective and accurate data center power models; 7) Draw support from communication and computing techniques (e.g., optical communication, virtual machine migration, placement optimization, etc.).

G. GREEN ICT PRINCIPLES

With the above introductions about green ICT enabling green IoT, we present the following general principles regarding green ICT and summarize all of them in Table 1.

1) *Turn off facilities that are not needed*. If the facilities are always working, it will consume much energy. However, if the facilities are only turned on when necessary, the energy consumption will be reduced. For example, *sleep scheduling* [42] is one of the widely used techniques for saving the energy consumption in WSNs, by making sensor nodes dynamically awake and asleep.
2) *Send only data that are needed*. Data (e.g., large sized multimedia data) transmission consumes quite a lot of energy consumption. Sending the data that are only needed by users, can significantly save the energy consumption. *Predictive data delivery* (e.g., [43]) based on user behavior analysis, is one possible method to provide only required data to users.
3) *Minimize length of data path*. This is also a straightforward method to reduce energy consumption. *Routing schemes* (e.g., [44]) considering the length of chosen data path could be energy-efficient. In addition, *network working mechanisms* (e.g., [45]) which cater to the routing requirement, are also potential ways to achieve much shorter data path.
4) *Minimize length of wireless data path*. Regarding minimizing length of wireless data path, *energy-efficient*

architectural designs (e.g., [46]) for wireless communication systems could be considered. Moreover, *cooperative relaying* [47] for wireless communications is also promising in energy efficiency, by using relay nodes to overhear the transmission and relay the signal to the destination node, resulting in significant diversity gains.

5) *Trade off processing for communications*. Combining data from multiple sources, *data fusion* [48] decreases the transmissions of similar data values, while transmitting more accurate data. Thus the energy efficiency is improved. As a new way of sensing the signal with a much lower number of linear measurements provided that the underlying signal is sparse, *compressive sensing* [49] is also able to enhance energy efficiency.

6) *Advanced communication techniques*. Towards green communications, advanced communication techniques are emerging. For example, employed at both the transmitter (Tx) and receiver (Rx), *multiple-input multiple-output (MIMO)* communication techniques [50] demonstrate improved spectral efficiencies in multipath fading environments, relative to their single-input single-output (SISO) counterparts. In addition, a *cognitive-radio (CR)* system [51] which is aware of its environment and can change its modes of operation (operating frequency, modulation scheme, waveform, transmitting power, etc.) via software and hardware manipulation, is able to improve spectrum-usage efficiency and minimize the problem of spectrum over-crowdedness.

7) *Renewable green power sources*. Different from traditional resources, a renewable resource (e.g., oxygen, fresh water, solar energy, timber, and biomass) is a resource which is replaced naturally and can be utilized again. Therefore, utilizing renewable green power sources will have a fundamental impact on minimizing the dependence on oil and the emission of CO_2 [52].

IV. SENSOR-CLOUD TOWARDS GREEN IoT

In this section, towards green IoT, we first present the overview of sensor-cloud. With that, recent developments regarding sensor-cloud are shown and the future sensor-cloud is envisioned.

A. OVERVIEW OF SENSOR-CLOUD

Defined by IntelliSys,[1] sensor-cloud is "an infrastructure that allows truly pervasive computation using sensors as an interface between physical and cyber worlds, the data-compute clusters as the cyber backbone and the internet as the communication medium" [13], [14]. According to MicroStrains,[2] sensor-cloud is "a unique sensor data storage, visualization and remote management platform that leverages powerful cloud computing technologies to provide excellent data scalability, rapid visualization, and user programmable analysis" [13], [14].

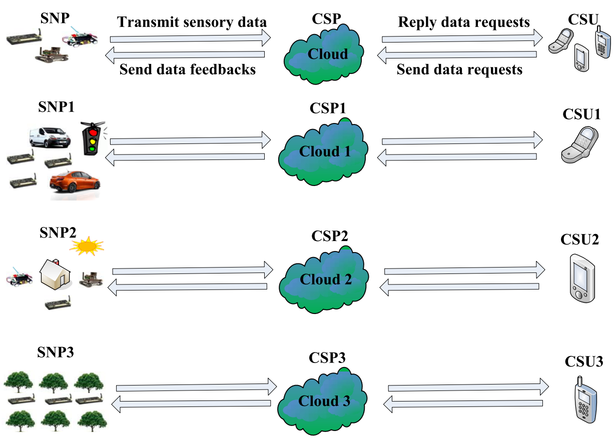

FIGURE 3. An example of sensor-cloud.

Attracting increasing interest from both academic and industrial communities, *sensor-cloud* [13], [14], [53] is actually a new paradigm, motivated by complementing 1) the ubiquitous data sensing and data gathering capabilities of WSNs as well as 2) the powerful data storage and data processing abilities of CC. Particularly, as presented in Fig. 3, the basic application model of sensor-cloud is to use the ubiquitous sensors (e.g., static sensors, mobile sensors, video sensors, etc.) offered by the SNP (sensor network provider) to collect various sensory data (e.g., temperature, humidity, traffic, house surveillance, etc.) about the surrounding environment. Then the sensory data is further transmitted to the cloud provided by the CSP (cloud service provider) for storage and further processing. After the cloud stores and processes the sensory data with data centers, the processed sensory data are delivered to the CSU (cloud service user) on demand. In this whole process, SNPs act as the data sources for CSPs. CSUs are the data requesters for CSPs.

With sensor-cloud integration, there are many favorable advantages [13], [14], benefiting the users and the WSN as well as the cloud. For instance, users can have access to their required sensory data from cloud anytime and anywhere if there is network connection, instead of being stick to their desks. The utility of WSN can be increased, by enabling it to serve multiple applications. The services cloud provides can be greatly enriched, by being able to offer the services that WSN provides (e.g., healthcare monitoring, environmental monitoring, forest fire detection, landslide detection, etc.). In particular, enhancing the performance (e.g., data processing speed, response time, visualization) of WSN with immense storage and processing capability of cloud, analytical results have shown that sensor-cloud could outperform a traditional WSN, by increasing the sensor's lifetime by 3.25% and decreasing the energy consumption by 36.68%. All these are very desirable for smart world and green IoT.

[1] http://www3.ntu.edu.sg/intellisys/index.html
[2] http://www.sensorcloud.com/system-overview

B. RECENT DEVELOPMENTS OF SENSOR-CLOUD

With respect to the *sensor-cloud framework*, [54] proposes a novel sensory data processing framework (named as NSDPF in this paper) to integrate WSN with mobile cloud. The problem researched is sensory data processing in sensor-cloud. The aim of NSDPF is to deliver desirable sensory data to the mobile users fast, reliably, and securely. Particularly, the sensor gateway and the cloud gateway are with data traffic monitoring, filtering, prediction, compression, and decompression capabilities. For offering data recommendation capability, the strong processing capacity of the cloud is adopted. For improving capacity, data encryption and decryption techniques are applied in the cloud, mobile devices, and sensor and cloud gateways. Analytical and experimental results are provided regarding the proposed NSDPF, in terms of enhancing the performance of sensor-cloud (e.g., enhancing the network lifetime, enhancing the storage requirement, enhancing the security and monitoring performance of WSNs, enhancing the security of the transmitted sensory data, reducing the traffic and bandwidth required for sensory data transmissions, reducing the cloud storage and processing overhead).

About the *energy efficiency of sensor-cloud*, two novel collaborative location-based sleep scheduling (CLSS) mechanisms are shown in [55] for WSNs integrated with MCC. Specifically, the focus of CLSS is enhancing the WSN lifetime, while still catering mobile users' data requests in sensor-cloud. For decreasing the integrated WSN's energy consumption, the detailed technique is dynamically changing the awake or asleep state of every sensor node, based on the mobile users' locations. CLSS1 targets at maximizing the integrated WSN's energy consumption saving, while CLSS2 also takes into account the integrated WSN's scalability and robustness. Theoretical and simulation results are both performed to demonstrate the effectiveness of the proposed CLSS mechanisms.

Concerning the *sensory data transmission in sensor-cloud*, a scheme named TPSS is designed in [56], aiming at reliably offering more useful data to mobile cloud from WSN. Particularly, the key issues that affect sensory data's usefulness and WSN's reliability are identified first. Then TPSS which consists of two main parts is introduced. Considering the time and priority features regarding mobile users' data requests, Part 1) is time and priority-based selective data transmission (TPSDT), for WSN gateway to selectively deliver more useful sensory data to the cloud. Part 2) is priority-based sleep scheduling (PSS) algorithm, for WSN to save energy consumption so that sensory data can be collected and delivered more reliably. Analytical and experimental results show the effectiveness of TPSS about enhancing sensory data's usefulness and WSN's reliability for sensor-cloud.

Regarding the *security of sensor-cloud*, a novel authenticated trust and reputation calculation and management (ATRCM) system is presented in [57], motivated by the following two critical security issues. Issue 1: Genuine CSPs and genuine SNPs could be impersonated by vicious attackers to perform communications with CSUs and CSPs, respectively. As a result, any service cannot be obtained by CSUs and CSPs from the fake CSPs and SNPs, while the trust and reputation of the authentic CSPs and SNPs are strongly decreased by these fake CSPs and SNPs. Issue 2: Lacking trust and reputation calculation and management of CSPs and SNPs, CSU may easily choose an untrustworthy CSP and CSP probably easily selects an untrustworthy SNP. Then the delivery of the service (from CSP to CSU, from SNP to CSP) owns an unacceptable large latency, or cannot be delivered successfully quite often, or could only be offered for a very short time period unexpectedly. To solve these two issues (i.e., authentication of CSPs and SNPs, trust and reputation calculation and management of CSPs and SNPs), they are with analysis first. With that, ATRCM is proposed, considering (i) CSP's authenticity and SNP's authenticity; (ii) CSU's attribute requirement and CSP's attribute requirement; (iii) the cost, trust and reputation regarding CSP's service and SNP's service. With detailed analysis and design as well as functionality evaluation results about ATRCM, it is presented that ATRCM is able to 1) assist CSU in selecting authentic and appropriate CSP; 2) help CSP choose authentic and desirable SNP.

Discussing *job scheduling in sensor-cloud*, [58] is interested in job scheduling for CC integrated with WSN, which is an unexplored topic. Particularly, the features of job scheduling about sensor-cloud are analyzed first and two popular and traditional job scheduling methods (i.e., Min-Min and Max-Min) are studied. Then two novel job scheduling methods (i.e., PTMM (priority-based two phase Min-Min) and PTAM (priority-based two phase Max-Min)) are put forward for CC integrated with WSN. Compared with Min-Min and Max-Min, extensive experimental results about PTMM and PTAM exhibit that they obtain shorter expected completion time (ECT) for CC integrated with WSN.

With the purpose to enhance the *quality of service (QoS) of sensor-cloud* about achieving sensory data from the cloud by users, TASC (trust-assisted sensor-cloud) is proposed in [59]. In TASC, trusted sensors (i.e., sensors with trust values that exceed a threshold) in WSN gather and transmit sensory data to the cloud. Meanwhile, trusted data centers (i.e., data centers with trust values that exceed a threshold) in cloud store, process and further on demand deliver the sensory data to users. Extensive simulation results present that TASC is able to greatly enhance the throughput and response time that users achieve sensory data from the cloud, in contrast to SCWTA (sensor-cloud without trust assistance).

With special attention to *sensor-cloud pricing* which is barely explored, five sensor-cloud pricing models (i.e., SCPM1, SCPM2, SCPM3, SCPM4 and SCPM5) are introduced in [60]. In particular, a sensor-cloud user is charged, considering 1) user's lease period; 2) needed working time of SC; 3) SC resources used by the user;

4) sensory data's volume achieved by the user; 5) SC path delivering sensory data to the user from the WSN, respectively. To discuss and demonstrate the performance of the proposed SCPMs, further analysis is also shown. The pricing schemes and conducted analysis in this work could be a very valuable guidance for future research concerning pricing in sensor-cloud.

C. FUTURE SENSOR-CLOUD

A straightforward comparison of the above recent research regarding sensor-cloud is shown in Table 2. From exploring these recent developments about sensor-cloud, it is observed that the research regarding sensor-cloud is still at its infancy, although sensor-cloud for green IoT is very promising. More interesting research regarding this area are expected to emerge.

TABLE 2. A summary of recent developments about sensor-cloud.

Scheme	Focus
NSDPF	Framework
CLSS	Energy efficiency
TPSS	Data transmission
ATRCM	Security
PTMM, PTAM	Job scheduling
TASC	QoS
SCPM	Pricing

Regarding the future sensor-cloud, we envision that the future sensor-cloud will evolve into *social-sensor-cloud (SSC)*, in which social networks (SNs) [61], [62], WSN and cloud connect and complement each other, as shown in Fig. 4. In *social-cloud*, integrating SNs and CC, there are already much research (e.g., [63]–[66]), in which the key idea is to share the cloud resources and services utilizing the relationships established between members of a SN. In SSC, leveraging SNs, not only will the sensor-cloud resources and services be shared, but also the SNs could be used to achieve better energy efficiency for sensor-cloud in the following ways.

- Sharing the sensor-cloud resources and services to other users with SNs, will substantially reduce the resources and services requested by the sensor-cloud users. As a result, the energy consumption of sensor-cloud can be decreased dramatically.
- The massive user behavior information in SNs, could be collected and analyzed as well as further utilized to enhance the energy usage in sensor-cloud (e.g., optimize the data gathering and data transmission in WSN, improve the data storage and data processing in cloud, etc.). In return, users' needs will also be better satisfied.
- Based on the amount of resource consumption and service usages created by a variety of users in SNs, the deployment of resources could be optimized and the waste of resources could be reduced in sensor-cloud.

In other words, the attendance of SNs could greatly help sensor-cloud fulfill green IoT.

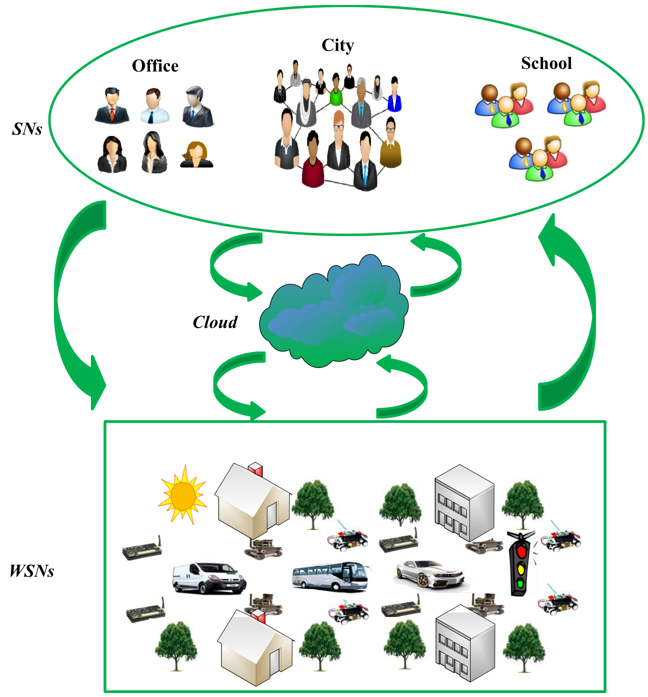

FIGURE 4. A vision of future sensor-cloud.

V. FUTURE RESEARCH DIRECTIONS AND OPEN PROBLEMS

The following future research directions and open problems concerning green IoT, are observed.

1) The *design of green IoT*, should be tackled from an overall system energy consumption perspective, subject to satisfying service objectives and achieving acceptable performance, QoS or quality of experience (QoE).
2) *Characteristics of different IoT applications and service requirements for these applications*, need to be better understood.
3) *Realistic energy consumption models* of different parts of IoT systems (e.g., WSN, core network, embedded system, CC, etc.), are needed.
4) With pervasive deployment of sensors, *a virtualized sensor as a service (SNaaS)* may be envisioned, in which users have access and control to their virtually private IoT.
5) Within the context of SNaaS, it is of interest to investigate *a) energy efficient system architecture; b) energy efficient service composition strategies; c) situation and context awareness regarding users and applications (e.g., learn and predict); d) energy efficient WSN management; e) energy efficient cloud management.*

VI. CONCLUSION

As an inspiring and latest guidance for research concerning smart world, this paper has discussed various technologies and issues with respect to green IoT, which plays a significant role in achieving a sustainable smart world. Specifically, the overview regarding IoT and green IoT has been performed. The technologies related to green IoT including five hot green ICT (e.g., green RFID, green WSN, green CC, green M2M, green DC) have been introduced, with the summary of general green ICT principles. In addition, bestowing particular attention to sensor-cloud which is a novel paradigm in green IoT, the latest developments about sensor-cloud have been shown and the future sensor-cloud has been envisioned. Finally, future research directions and open problems regarding green IoT have been presented.

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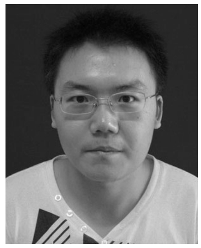

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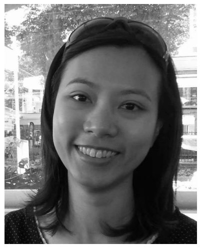

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