Energy-Efficient Industrial Internet of Things: Overview and Open Issues

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***Abstract*—The last few decades have witnessed an explosive growth of the Internet-of-Things (IoT) systems, which provide ubiquitous sensing and computing services. When adopted in industrial and manufacturing environments, IoT is referred to as the industrial IoT (IIoT), which has attracted increasing research attention. Energy efficiency is one of the most important research topics in green IIoT, as 1) the limited resource can significantly affect the lifetime of IIoT systems and 2) massive sensors, devices, machines keep consuming a considerable amount of energy, and increasing the carbon footprint. In this article, we present a comprehensive survey on energy-efficient communications and computation mechanisms in IIoT systems (such as smart grids). We categorize the existing works, review, discuss, and compare the works to explore their pros and cons. We also discuss the open issues and research challenges, considering the recent 5G communications and edge computing trends.**

***Index Terms*—Energy efficiency, green communications and computing, industrial Internet of Things (IIoT), Internet of Things (IoT).**

I. Introduction

IN THE last few decades, Internet of Things (IoT) has gained widespread attention and acceptance as a novel paradigm due to the enormous progress obtained in the wireless communications and microelectronics. IoT, when applied to the industrial environments, is termed as industrial IoT (IIoT) [1]. As an essential subset of the IoT systems, IIoT has attracted much attention from both industry and academics as cutting-edge technology for the manufacturing industries, and spawned lots of novel concepts related to industrial scenarios, such as surveillance [2], sensor validation [3], digital twins [4], etc.

IIoT connects massive mobile digital devices, manufacturing machines, industrial equipment, etc. [5]. The devices include RFID tags, CRFID tags, ZigBee/LoRa-based sensors, etc. Those devices keep generating tremendous data and signals used for sensing, controlling, system maintenance, and data analysis. The communication and computation tasks on the "things" in IIoT, apparently, will consume substantial energy. Considering the limited resources on the IIoT devices [6], energy efficiency in IIoT is a crucial problem in a number of innovative IIoT systems such as smart grids [7], smart cities [8], and electronic health [9], [10]. Smart grid is a typical IIoT system in which massive monitoring sensors are placed with the electricity meters to continuously measure, transmit condition data and control messages. The sensing and communication tasks are highly energy-consuming and directly affect the lifetime of the smart grid system [11]. In other harsh industrial scenarios, such as the production industry and mining, energy efficiency is also a critical issue. For example, LotTrack is an RFID system that utilizes RFID tags and controllers for tracking plastic wafer boxes and wafer cassettes in automatic semiconductor manufacturing [12]. The energy wasted in RFID identify will be huge. Perceiving Mine [13] is a communication and monitoring system, which utilizes Wi-Fi/ZigBee/RFID sensors and controllers for in-mine mobile communications, personal location monitoring, and wireless access for portable devices. The energy efficiency in communication is a key factor to prolong the lifetime of such IIoT systems.

Specifically, the impact of energy efficiency in IIoT is twofold. First, from the devices' perspective, as the devices are resource constrained in both computation and communication, energy consumption may shorten the lifetime of IIoT [14]. Second, the sensing, computing, and communicating takes executed by the IIoT devices can also lead to an increasing carbon footprint from the whole system's perspective [15]. For example, as reported in [16], the amount of carbon dioxide emissions from the cellular networks will be 345 million tons by 2020, and it is expected to increase in the later years.

We summarize the existing survey works and compare our work with them. Table I lists the representative survey works pertaining to the IIoT context. Sisinni *et al.* [1] and Boyes *et al.* [18] reviewed the relationship and difference between IoT, IIoT, and Industry 4.0. Sisinni [1] presented the opportunities and challenges in terms of energy efficiency, real-time performance, coexistence and interoperability, security, and privacy. After presenting the definition of IIoT, Boyes *et al.* [18] proposed an analytical framework for characterizing IIoT devices. Liao [4] performed a systematic literature review (SLR) focused on the IIoT academic achievements. According to the insights obtained from the SLR, the authors conclude and discuss the current

Manuscript received November 26, 2020; revised February 20, 2021; accepted March 3, 2021. Date of publication March 18, 2021; date of current version July 26, 2021. This work was supported by the National Natural Science Foundation of China under Grant 61972075, Grant 62071105, and Grant 61972074. Paper no. TII-20-5353. *(Corresponding author: Zhiwei Zhao.)*

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Digital Object Identifier 10.1109/TII.2021.3067026

TABLE I
EXISTING IIOT SURVEY AND ITS FOCUS

Refs.	Focus
[1]	Energy efficiency, coexistence, security and privacy
[4]	A literature review of IIoT systems in a systematic manner
[6]	Communication protocols and data management schemes
[17]	Communication technologies in IIoT
[16]	characteristics and classification of IIoT systems
[5]	Energy consumption issues in the context of industry 4.0
[18]	Blockchain-based IoT and IIoT
[3]	A survey of IIoT as a component of cyber-physical systems
[19]	Edge computing in IIoT

limitations of IIoT and future research trends. The research work in [6] gives a new definition of IIoT and review the state-of-the-art research efforts from three research areas: architectures and frameworks for IIoT, communication protocols and data management schemes. Younan *et al.* [17] introduced the state-of-the-art challenges and recommended technologies in IoT. Specifically, Younan *et al.* [17] studied the impacts of information communication technologies on smart transportation and healthcare. Silva *et al.* [5] proposed a systematic literature review on the energy consumption and bring up an energy taxonomy in the scope of Industry 4.0. Although focusing on the energy consumption in Industry 4.0, Silva *et al.* [5] put its most efforts on the taxonomy of energy consumption rather than discussing the energy-efficient mechanisms of IIoT in detail. Other researchers present their review of IIoT in some specific perspectives, such as blockchain-based IIoT [19], cyber-physical systems for IIoT [3], and edge computing in IIoT [20]. According to these surveys, lots of IIoT applications need to run for years on batteries, which makes energy efficiency an important issue. However, the energy-efficient mechanisms in IoT can not straightly be applied to IIoT due to the communication and computation requirements difference in IoT and IIoT (will be explained in detail in Section II-A). Compared with the abovementioned works, our survey is carried out from the perspective of energy-efficient mechanisms in IIoT, which consists both communications and computations.

This article aims at providing a comprehensive survey of the energy-efficient system designs of IIoT. According to IIoT's working process, the energy consumption consists of three main parts: communication, computation, and sensing. Considering that the energy consumption of sensing is mainly determined by the hardware specifications, the existing works mostly fall into two lines: reducing the communication overhead and reducing the computational overhead.

We then categorize existing works into two groups: energy-efficient communication schemes and energy-efficient computing schemes. In each of the abovementioned categories, we review the state-of-the-art works and compare them in terms of their principles and energy efficiency. After that, we proceed to discuss the open issues and challenges for energy efficiency of IIoT systems. The main contributions of this article are summarized as follows.

1) We provide a comprehensive and easy-to-follow categorization for the literature of the energy-efficient mechanisms for IIoT systems.
2) We have made detailed discussions about the differences between IoT and IIoT, for better districting the energy efficiency mechanism in IIoT from that in IoT. We have also offered a qualitative comparison between IoT and IIoT in terms of communication and computation.
3) We review the state-of-the-art mechanisms in improving the energy efficiency of the IIoT systems in terms of both communication and computation. Besides, we present comprehensive discussions and comparisons to reveal the pros and cons of different works in different application scenarios.
4) The open research issues and challenges are discussed along with the future directions, which could shed light on the implementation of energy-efficient IIoT.

The rest of this article is organized as follows. Section II presents the four-tier category of the energy-efficient mechanisms in IIoT. Section III presents the energy-efficient mechanisms focusing on the IIoT communications, while IV focuses on the IIoT computations. In Section V, we discuss the open issues, challenges and research trends in energy-efficient designs of IIoT. Finally, Section VI concludes this article.

II. COMMUNICATION AND COMPUTING IN IOT AND IIOT

In this section, we categorize the existing works according to the distinct features of different types of IIoT systems. Intuitively, the energy is mainly consumed by three modules of the IIoT devices: sensing, communication, and computation. As energy computing of sensing is usually determined by the application area, in this article, we mainly focus on energy consumption of communications and computations in IIoT. We first discuss the differences between IoT and IIoT in terms of communications and computations. Then, we introduce the communication and computation in IIoT.

A. IoT and IIoT

As a subset of IoT, IIoT shares many common technologies with IoT, in terms of sensors, cloud platform, connectivity, analytics, to name a few. However, working scenarios, aims, and application requirements make IIoT distinct from IoT and, thus, lead to different designations on communication and computation. Comparing to the aims, unlike IoT, which is often assumed to provide general human-centric consumer services, IIoT is production-oriented and designed to reduce production cost and promote manufacturing efficiency. Comparing to the scenarios, IoT networks are often deployed at home/office scenarios, involved with smart consumer electronic devices such as smartwatches, smartphones, etc. As a contrast, IIoT networks often cover larger areas (industry/city scale), with a larger number of devices (lots of industrial assets such as sensors, actuators, controllers, and other critical industrial equipment) than IoT. Application requirements are another key difference between IoT and IIoT. IIoT puts more effort into security and reliability than IoT. The reason is that the failures on IIoT devices (such as controllers and other critical industrial equipment) may cause life threatening or other emergency situations [1]. Besides, the delay is another crucial attribute of IIoT, as the timeliness of data

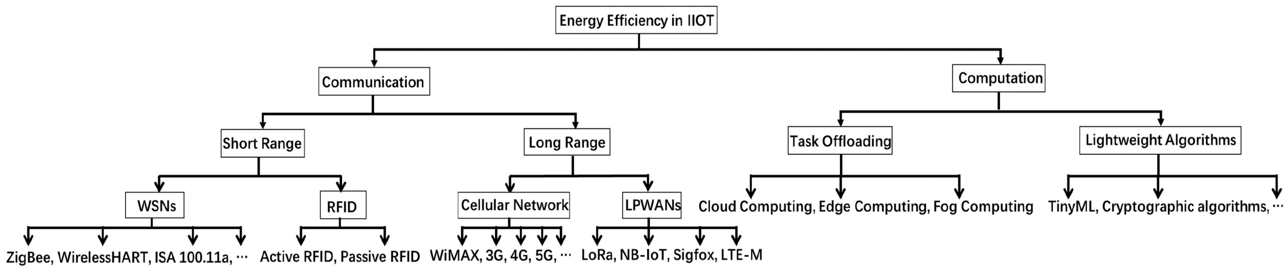

Fig. 1. Key enabling technologies surveyed in this article.

TABLE II
COMPARISON BETWEEN IoT AND IIoT

		Consumer IoT	Industrial IoT
Feature		Consumer-oriented	Production-oriented
Aim to		Provide convenience and improve life quality	Reduce production cost and promote efficiency
Communication	Devices	Smart consumer electronic devices	Industrial assets
	Network scale	Small to medium	Large to very large
	Delay-tolerance	Medium to high	Low
	Main network type	WLAN, Cellular network	WPN, WLAN, Cellular network, LPWAN
	Technologies	Wi-Fi, Bluetooth, 3/4/5G, etc.	IEEE 802.15.4, RFID, 3/4/5G, LoRa, etc.
Computation	Data volume	Medium to large	large to Very large
	Delay-tolerance	Medium to high	Low
	Data security requirements	Medium	High
	Task complexity	Medium to high	High to very high
	Resource allocation	High dynamics	Stable

is essential in industrial monitoring and control networks. For IoT, most IoT applications are delay insensitive, except for health monitoring applications. These key differences between IoT and IIoT result in their unique communication and computation requirements, which in turn lead to the different energy-efficient mechanisms. The differences of communication and computation requirements are summarized in Table II.

Comparing to the network scales, the network scales of IIoT are generally larger than IoT. A typical IoT network interconnects tens to hundreds of smart consumer electronic devices such as smart glasses, smartwatches. By contrast, an IIoT network involves hundreds to thousands of industrial assets such as sensors, actuators, controllers, and other critical industrial equipment. Besides, due to the timeliness requirements of data in IIoT, IIoT is more sensitive to the communication delay than IoT in most cases. In addition, IIoT includes more network types than IoT. The major network types of IoT are WLAN and cellular networks, adopting Wi-Fi, Bluetooth, and 4/5G technologies. IIoT networks further include low powered wide area network (LPWAN) and WPN.

Typical application scenarios of IIoT include smart logistics, remote maintenance, and intelligent factories. These applications will generate a large amount of data, with strict real-time requirements. Thus, the computation tasks of IIoT are often complex and delay sensitive. By contrast, the most typical application scenarios of IoT are smart home, smart office, and indoor localization. The computation tasks of these applications require fewer data and are delay tolerated, with less complexity. Besides, industrial applications are more sensitive to data security than IoT. Although IoT and IIoT basically adopt same computing frameworks, such as edging computing, clouding computing, to name a few, the resource allocation strategies remain different. A key difference is that the resource allocation strategies of IoT need keep adjusting dynamically as the users move, comparing with IIoT, due to the strong mobility of user requests in IoT.

B. Communication and Computing in IIoT

As shown in Fig. 1, the energy-efficient mechanisms in communications can be categorized into different groups in terms of the specific transmission technologies of the IIoT system. According to the transmission range, we mainly consider the short-range IIoT systems and the long-range IIoT systems and discuss the energy efficiency related issues. Same as the classification in [21], we regard these communication systems as short-range communication systems, in which the transmission range is no more than hundreds of meters, and the others are categorized as long-rang communication systems. In short-range IIoT systems, the communication range of devices is highly limited, which leads to that the systems either need to work in proximity to humans or work in a multihop manner. The underlying communications technologies mainly include RFID, ZigBee [22], WirelessHart [23], ISA 100.11a [24], Wi-Fi, Bluetooth, etc. A qualitative and quantitative comparison between the abovementioned technologies is given be Table III.

For works on short-range IIoT systems, we mainly concentrate on the RFID (passive and active) and wireless sensor networks (WSNs), which are two essential types of IIoT systems. There are wide applications working in such IIoT systems, such as intelligent manufacturing, supply chain tracking, retail item management, and environmental monitoring [25]. For WSNs, the IEEE 802.15.4 standard is the most popular standard used in IIoT systems. The IEEE 802.15.4 standard specifies physic layer (PHY) and medium access control (MAC) sublayer characteristics, aiming at addressing low-rate wireless personal area networks in low cost, low power consumption, and low data rate IIoT applications. The key features of IEEE 802.15.4 are as follows: 1) low data rates of 250, 40, and 20 kb/s; 2) low power consumption with power management; 3) automatic network (star or multihop network) establishment by the coordinator; 4) low latency support for latency-critical devices; 5) 27 channels allocated with 16 channels in the 2.4 GHz band, 10 channels in the 915 MHz band, and 1 channel in the 868 MHz band [26]. Based on IEEE 802.15.4, various WSNs protocols are developed

TABLE III
COMPARISON BETWEEN SHORT-RANGE AND LONG-RANGE COMMUNICATION TECHNOLOGIES

Technology		Cover range	Carrier frequency	Modulation type	Channel bandwidth	Data rate	Typical applications
RFID		**Short-range** (< 15m)	LF: 125KHZ HF: 13.54MHz UHF: 850/910MHZ Microwave: 2450GHz/5800GHz	Backscatter	**Narrow** (~100KHz)	**Low to medium** (1kbps~1MHz)	manufacturing industry, Logistics management
IEEE 802.15.4		**Short-range** (< 1km)	8685MHz /915MHz/2.4GHz	O-QPSK, DSSS, BPSK	**Medium** (2/5MHz)	**Low** (20/40/250kbps)	industrial control
Cellular Network	3G	**Long-range** (1~10km)	1880MHz-1900MHz 2010MHz-2025MHz	CDMA	**Medium to wide** (5/15/25MHz)	**Medium to high** (300kbps~2Mbps)	Smart home/office Driverless cars Video surveillance
	4G	**Long-range** (1~10km)	1880-1900MHz, 2320-2370MHz, 2575-2635MHz	64-QAM 256-QAM	**Wide** (15/25/50/160MHz)	**High** (500Mbps~1Gbps)	
	5G	**Long-range** (10m~1km)	3300-3400MHz 3400-3600MHz 4800-5000MHz	512-QAM 1024-QAM	**Wide** (100/160/800MHz)	**High** (~10Gbps)	
LPWAN	LoRa	**Long-range** (~10km)	433/470/868/915/920 MHz	CSS	**Narrow** (125/250/500KHz)	**Low** (<=27kbps)	Smart agriculture, smart metering, smart parking
	NB-IoT	**Long-range** (~15km)	GSM/LTE channel	OFDMA SC-FDMA	**Narrow** (180KHz)	**Low** (~50kbps)	
	Sigfox	**Long-range** (~10km)	868//902MHz	UNB, BPSK	**Narrow** (192kHz)	**Low** (~100bps)	
	LTE-M	**Long-range** (~10km)	GSM channel	QPSK, 16-QAM	**Narrow** (180KHz)	**Low to medium** (375kbps/1Mbps)	

for meeting different IIoT application requirements, such as ZigBee, WirelessHart, ISA 100.11a, etc. [27]. For RFID, a typical RFID system is composed of an RFID reader and RFID tags. According to the resources of energy supply, RFID tags can further be divided into two classes: active tags and passive tags. Active tags use their own energy to modulate signals, while passive tags use the energy aroused in the antenna by the reader's signal based on the electromagnetism induction phenomenon [28]. According to the working frequency, RFID tags can also be categorized as: low frequency (LF) RFID, high frequency (HF) RFID, ultrahigh frequency (UHF) RFID, and microwave RFID [29].

According to the network types, the long-range IIoT systems are further divided into cellular networks and LPWANs. The communication technologies of cellular networks include WiMAX, 3G, 4G, 5G, etc. In cellular networks, we put our efforts to energy-efficient 5G IIoT systems, as the integration of 5G and IIoT is most widely researched and attractive in recent years. LPWANs technologies include LoRa, NB-IoT, Sigfox, etc. In this category, we mainly focus on LoRa due to its openness and wide applications. Unlike traditional communication technologies, LoRa uses the chirp spread spectrum (CSS) modulation and promises to be robust against channel interference, multipath, and Doppler effect [30]. The key parameters that have significant impacts on the energy efficiency and reliability of LoRa communications include spreading factor, bandwidth, coding rate, and transmission power [31]. Among them, there are three characteristics of LoRa as follows.

1) *Long-range*. LoRa claims several kilometers of communication range.
2) *Low powered*. The lifetime of LoRa nodes is about several to ten years.
3) *Low data rate*. The max data rate of LoRa is about 27 kbit/s [32].

LPWAN is the LoRa original MAC protocol, which is based on pure ALOHA protocol. LPWAN consists of three types: Class A, Class B, and Class C [33]. The existing works on LoRa mainly focus on designing more efficient MAC protocols and network-wide parameter optimizations. Therefore, in this article, we mainly focus on the abovementioned two research topics.

Specifically, the transmission range is the only standard to distinct short-range and long-range IIoT systems. Although differing in transmission range, two communication technologies may have the same carrier frequency or bandwidth. For example, both Zigbee and LoRa work in industrial scientific medical band, and may with the same bandwidth.

For computation technologies, there are two high-level lines of works: lightweight algorithms and task offloading. Most existing works are implemented in a lightweight manner due to the limited resource of the IIoT devices. The lightweight mechanisms include: TinyML, lightweight cryptographic algorithms, etc. The researches of TinyML are target at integrating machine learning (ML) based mechanisms within energy-constrained devices such as IIoT devices [45]. For meeting the security requirement of IIoT systems, the lightweight cryptographic algorithm not only guarantees the IIoT system security but also reduces the energy consumption of IIoT devices, as another research focus [46]. The other lightweight mechanisms include measurement and calculation of the link features, link estimation, routing decisions, network coding, etc. For example, Zhao *et al.* [47] proposed a lightweight estimation scheme for link correlation, which was defined quite complex for multiple links.

The other line of work, task offloading, emerges along with edge computing, fog computing, and cloud computing. Cloud computing is trusted to enable ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., bandwidth, storage, CPU, services, etc.). As one of the key enabling technologies of IIoT, cloud computing greatly changes traditional industries by providing on-demand computing and storage services with high reliability, scalability, and availability for IIoT systems. Edge computing, which is regarded as the complement of cloud computing, tends to provide elastic resources at the edge of the network toward applications demanding computational-intensive tasks with high bandwidth and ultralow latency [48]. In edge computing, the computation resources are deployed at the edge of the network, so that the edge devices can offload their computational-intensive tasks to the edge server, where the tasks will be executed and the results will be returned. The so called computation offloading or task offloading is considered as an efficient way to make the devices more "smart". Through the edge computing paradigm, the energy of edge devices such as IoT devices will be saved and the task latency will be decreased [49], [50]. In addition to the offloading, edge nodes can also perform data storage, caching, and processing, as well as distribute requests and delivery services to users [51]. Fog computing frameworks have also received increasing interest in the development of IIoT. We consider the main difference between edge computing and fog computing is that the edge computing focuses more on the side of things, while fog computing focuses more on the side of infrastructure [52], [53]. As a consequence, in this article, we regard them as two distinct frameworks, and present how to obtain energy efficiency for IIoT via the development of all three frameworks.

III. Energy-Efficient Communications in IIoT

As we have briefly presented, there are different types of wireless communication technologies used in IIoT, such as RFID, ZigBee, WirelessHART, ISA 100.11a for short-range IIoT, and LoRa, 5G for long-range IIoT. The energy consumption of communications takes a major portion of the overall energy consumption of the IIoT systems. There are several major reasons. First, the wireless unreliability can lead to the fluctuation of the wireless links, channel collision, congestion, signal attenuation, etc. Each one of these issues will potentially lead to transmission failure, further requesting extra energy for retransmission. Second, due to the broadcast nature of wireless communications, the channel competition and the resulting inefficiency of routing protocols also will aggravate the energy consumption. For improving the communication efficiency of IIoT, there are a large number of studies aiming to save the energy in transmission from different communication technologies. In this section, we will briefly overview and categorize the energy-efficient mechanisms designed for short-range and long-range IIoT systems, respectively.

A. Short-Range IIoT Systems

In this section, we discuss the energy efficiency issues in the IIoT system using short-range communication technologies. Table IV shows the energy-efficient mechanisms based on short-range IIoT systems. According to the scenarios, we divide these work into three categories: based on passive RFID, based on active RFID, and based on sensor networks.

For passive RFID, some researches aim to modify the EPC Class1 Gen2 standard, which is widely used in RFID system, to improve communication efficiency between readers and RFID tags [34], [35]. In the EPC Class1 Gen2 standard, the reader initializes an identification process by broadcasting a query command. After receiving the query command, the tags in the vicinity respond to the reader with their IDs. However, collisions may happen when two or more tags respond at the same time. The collision wastes not only the energy of readers, but also the energy of RFID tags. Accordingly, the anticollision mechanism becomes a significant way to save energy and improve the energy efficiency of RFID systems. Specifically, Su *et al.* [34] reviewed and compared the existing anticollision algorithms in UHF RFID. For improving the energy efficiency of anticollision algorithms in UHF RFID, Su *et al.* [34] proposed a novel energy-efficient anticollision algorithm that consists of three parts: tag cardinality estimation, adaptive frame size calculation, and frame size adjustment strategy. By combining tag cardinality estimation and adaptive frame size calculation, the proposed algorithm can ascertain the optimal frame size and improve the overall energy efficiency. In [35], focusing on both the time and energy efficiency of the DFSA algorithm, the authors propose an algorithm, which uses looking-up-tables to reduce the cardinality estimation complexity and adaptively configures the frame size according to different parameters setting. Xu *et al.* [36] considered the interference from multiple readers, which may lead to failing identification and wasting energy. For addressing this issue, the authors design an algorithm called automatic power stepping (APS), which can dynamically adjust the power level of readers according to the estimated tag number,

For active RFID, Lee *et al.* [37] investigated the overhearing problem, which describes a scenario where some tags are awakened by the reader accidentally. These accidentally awakened tags will waste their energy to stay active, with no work to do. In order to reduce the energy consumption caused by overhearing, the authors design a protocol called Reservation Aloha for No Overhearing, which informs tags of their effective communication intervals. In this way, the energy wasting can be reduced. Zhang *et al.* [38] divided the collision into two types: reader-tag collision and reader-reader collision. For improving the energy efficiency in such a system, Zhang *et al.* [38] proposed an energy-efficient tag searching protocol, named ESiM. In such a protocol, each tag is only required to exchange one bit data with readers, so that the energy efficiency can be greatly improved.

TABLE IV
ENERGY-EFFICIENT MECHANISMS IN SHORT-RANGE COMMUNICATION TECHNOLOGIES

Technology	Problem	Protocol	Idea	Method	Reference
Passive RFID	Tag collision	EPC Class1 Gen2	Energy-efficient anti-collision algorithm in EPC Class1 Gen2 standard	Energy-efficient algorithm with 1) tag cardinality estimation 2) adaptive frame size calculation, 3) frame size adjustment strategy	[28]
			Improve both time and energy efficiency of EPC C1 Gen2 standard	Reduce the carnality estimation complexity; adaptively configure the frame size	[29]
	Reader collision	Not specified	Save energy while reducing the interference from multiple readers	Automatic power stepping (APS), dynamically adjusts the power level according to the tag number	[30]
Active RFID	Overhearing		Overcome the overhearing problem	Inform tags of their effective communication intervals	[31]
	Reader -tag and -reader collision		Anti-collision: 1) reader–tag collision, 2) reader-reader collision	Two energy-efficient tag searching protocols: ESiM and TESiM	[32]
Sensor Network	Channel election	ISA 100.11a	Channel election of ISA 100.11a	Propose a Probabilistic calculation model for selecting high quality channels	[33]
	Routing	WirelessHART	Energy balance routing in WirelessHART	Interactively collects the energy consumption for each node and generates routing path	[34]
	Data aggregation		Data aggregation framework for WirelessHART	Jointly consider link quality, residual energy, transmission frequency for parent node election and light-weighted time-slots schedule mechanism	[35]
	Data Collection	Not specified	Energy-Efficient Sensor Data Collection Approach for Industrial Process Monitoring	Adaptive data collection mechanisms that allow each sensor node to adjust its sampling rate, optimizing its energy consumption	[36]
	Routing		An Energy Efficient and QoS Aware Routing Algorithm Based on Data Classification	Classify the industrial sensing data; route different data with different routing strategies to save energy	[37]
	Schedule	IEEE 802.15.4/ZigBee	Energy Efficient Schedule for Cluster Tree WSN	Present a novel heuristic scheduling algorithm that is based on formulations of graph theory problems.	[38]

However, considering the long searching time in ESiM, the authors further improve the time efficiency and propose a modified protocol named TESiM, with the energy efficiency tradeoff.

In IIoT WSNs scenario, there are researches mainly focusing on channel selection, routing, data aggregation, data collection, and scheduling. Serizawa *et al.* [39] improved the energy efficiency of ISA 100.11a standard through the proposed channel selection mechanism called "adaptive channel diversity" (ACD)? Due to the random frequency channel hopping, ISA 100.11a devices may access low-quality channels and degrade its performance. The key idea of ACD is using the probabilistic calculation model to select the high-quality channel by continuously monitoring the quality of all channels.

Han *et al.* [40] and Li *et al.* [41] focused on enhancing WirelessHART. As the uneven premature energy depletion of individual nodes shortens the lifetime of the whole WirelessHART network, the research work in [40] presents an energy-balancing routing algorithm. Once the hierarchical network topology is constructed, the algorithm collects the energy consumption for each node and generates routing paths iteratively. The main advantage of the algorithm is that it fully conforms to the WirelessHART standard and could be directly applied to commercial products. Data aggregation is trusted to reduce the traffic and prolong the lifetime of the WSNs. However, due to the multichannel time synchronized mesh protocol and the superframe-based communication slot scheduling in WirelessHART, existing data aggregation techniques cannot be applied directly to WirelessHART networks. Li *et al.* [41] proposed a data aggregation framework for energy-efficient WirelessHART communication. For energy fairness and high packet reception ratio in the network, the authors consider link quality, residual energy as well as transmission frequency in the link selection for upload path so that high residual energy nodes will be selected as parents nodes.

Harb and Makhoul [42] aimed to improving the energy efficiency in sensor data collection for industrial process monitoring. The authors propose adaptive data collection mechanisms to adjust sensors' sampling rate to the variation of environment. By this way, the authors reduce the energy used for both sampling and data transmission without sacrificing the accuracy of data collection.

Different from the energy-balanced routing in [40] and [43] focus on timeliness-based routing that routes different types of data packet by different routing strategies. The authors classify the industrial sensed data into three kinds: high timeliness event data, low timeliness event data, and periodic data. When routing lower timeliness event data, the proposed routing strategy consumes less energy with the sacrifice of more delays.

Ahmad and Hanzlek [44] researched the cluster scheduling respecting collision avoidance problem for cluster tree WSN, such as IEEE 802.15.4-based/ZigBee networks. In such networks, sensor nodes are divided into different clusters and maintain sleep mode to save energy until they are scheduled and allocated time slots. The key problem to improving energy efficiency is

TABLE V
ENERGY-EFFICIENT MECHANISMS IN 5G

Scenario	Idea	Main Contribution	Refs
Industrial automation	High-accurate state estimation for saving the whole system energy	An estimation-transmission codesign for adaptive resource allocation and on-demand information transmission	[41]
Green communication in IIoT	Cooperative Caching	With the constraint that the quality of service, to reduce the average energy consumption by Cooperative Caching	[42]
	power optimization in 5G networks	Power allocation and relay selection strategy	[43]
Heterogeneous networks	Improving energy efficiency	Find the trade-offs between the energy minimization and capacity maximization in a multi-layer HetNet	[44]

to maximize the time when the clusters are in a sleep mode without missing data deadlines. The authors prove the problem is NP-hard and propose an effective heuristic scheduling algorithm that scales well with the size of the network.

B. Long-Range IIoT Systems

For long-range IIoT systems, We focus on 5G in cellular networks and LoRa in LPWANs, for the reason that both of them are the research emphasis in their domains.

The emergence of 5G cellular networks dramatically change the connectivity landscape of IIoT devices. Promising low end-to-end delay (tens of milliseconds), high data rate, and large bandwidth, 5G offers excellent support for IIoT connectivity. Alone with 5G, private 5G shows more potential for integration with IIoT. A private 5G network is a particular realization of the 5G system designed and configured for private, which means nonpublic-use by an exclusive group of users [67]. Comparing with 5G, the advantages of private 5G is that it further offers dedicated coverage, exclusive capacity, intrinsic control, customized service, and dependable communication [68]. There are lots of efforts attached to the energy efficiency in 5G-IIoT.

As shown in Table V, Lyu *et al.* [54] introduced an industrial automation scenario, where the state of process control is monitored by spatially distributed sensors and 5G machine-type communication enabled IIoT. The authors aim at high-accurate state estimation over 5G enabled IIoT. To overcome the challenges of complex industrial wireless environments and limited communication resources, the authors propose a codesign framework to integrate the state estimation with the wireless information transmission. Based on this framework, a hierarchical transmission-estimation approach is come up for improving both the estimation accuracy and energy efficiency.

In the green communication IIoT situation, Duan *et al.* [55] proposed a space-reserved cooperative caching scheme for IIoT. In such a scheme, the cache space in a base station is divided into two parts: 1) the first part is used to store the prefetched data from the servers ahead of the device request time and 2) the second part is reserved to store the temporarily buffering data in the wireless transmission queue at the device request time. The main challenge is to obtain the optimal proportion of two parts so that the system can reach perfect tradeoff between service quality and average energy consumption. The authors formulate the problem as a concave one-variable real function and solve it by a golden section algorithm. Abrol *et al.* [56] considered a heterogeneous 5G network topology consisting of low power and high power nodes in green communication. For improving energy efficiency, the authors present a three-layered system model, which uses a relay selection strategy for power optimization. To answer the power optimization question, the authors propose a hidden Markov model to train and maintain the base station, relay, and small access point for getting a probabilistic power allocation mechanism. An adaptive modulation scheme is further introduced to dynamically adjust the power consumption. Chavarria-Reyes *et al.* [57] mainly focused on multistream carrier aggregation (MSCA) technology for heterogeneous networks (HetNets) in 5G wireless systems. As previous studies neglect the energy efficiency of MASC, the authors study the energy minimization problem in a multilayer HetNet. The authors first prove the problem is a nonconvex optimization, and then solve it through a generalized linear-fractional program and a bisection method.

LPWANs are garnering increasing attention from the research community in recent years. As one of the key communication technologies in LPWANs LoRa is widely researched in recent years. And there are lots of works about improving energy efficiency in LoRa. As shown in Table VI, according to working in which layers, these works can be divided into four categories: PHY work, MAC work, upon MAC work, and MAC and PHY work.

In the physic layer, there are three main fields that most studies concentrate on, including parameter management, signal demodulation, and packet recovery. As the transmission parameters have significant impacts on the energy efficiency and reliability of LoRa communications, parameter management gains a large potential to improve the energy efficiency of LoRa networks. Ochoa *et al.* [58] investigated the energy consumption in LoRa with various LoRa configurations for star and mesh network topologies, respectively. According to the investigation, the authors propose a parameter choosing strategy for star and mesh network topologies, respectively.

Besides, recovering original packets from collided packets also improves the energy efficiency of LoRa networks, due to saving the energy of retransmission. Eletreby *et al.* [59] worked in packets recovery in LoRa transmission. For solving this problem, Eletreby *et al.* [59] took the hardware imperfections as the unique information of different LoRa nodes to separate the collisions between LoRa packets. Eletreby *et al.* [59] also enabled a longer transmission range by a collaborative mechanism between LoRa nodes.

TABLE VI
ENERGY-EFFICIENT MECHANISMS IN LORA

Work Layer	Idea	Main Contribution	Refs
PHY	Parameter management	Optimize the packet error rate fairness by set different transmission parameters	[45]
	Packet recovery	Using hardware information to help to recover LoRa chirps	[46]
	Signal demodulation	A demodulation scheme which can demodulate the sub-Nyquist sampling chirps	[47]
MAC	New MAC protocol	Centralized-synchronous MAC protocol	[48]
Upon MAC	Transmission scheduling	A scheduling scheme to reduce collision	[49]
MAC and PHY	Energy fairness	Network resources allocation to fair energy consumption of LoRa nodes	[50]
	Backscatter system	Design an ambient, passive LoRa backscatter system	[51]
		Design long-range LoRa backscatter system	[52]
	Adaptive configuration	Adaptive data rate (ADR) mechanism	[53]

An energy-efficient LoRa signal demodulation method can also improve the energy efficiency of LoRa networks. For saving the energy consumed by receiving packets, Xia *et al.* [60] investigated the LoRa chirps modulation and demodulation processes in detail. The authors observe that the hardware of LoRa radio will cause phase jitters on modulated chirps. Based on this observation, the authors design a demodulate scheme that can achieve sub-Nyquist sampling and signal demodulation, by taking the timing information of phase jitters and frequency leakages as physical fingerprints. By decreasing the sample rate in signal demodulation, the scheme can save the energy used for packet reception.

For the MAC layer, considering that the MAC layer (LPWAN) of LoRa is simply based on pure ALOHA, there are researchers who study in designing a new MAC layer for LoRa. Hassan *et al.* [61] proposed a MAC protocol named MoT, which is a centralized-synchronous time-slotted protocol. In MoT, a central base station will coordinate and schedule multiple time-slots for LoRa nodes. Every LoRa node will only wake-up transmit or receive in its own transmit or receive slots. By this way, the authors claim that MoT can extend nodes' lifetime up to four times longer than the contention-based device.

Same as Hassan [61] and Haxhibeqiri [62] aimed to reduce the channel contention caused by LPWAN MAC layer and improve the throughput. However, Haxhibeqiri *et al.* [62] worked upon the MAC layer. Haxhibeqiri *et al.* [62] proposed a synchronization and scheduling mechanism for LoRaWAN networks consisting of LPWAN class A devices. By scheduling the downlink and uplink transmission of LoRa nodes, this scheme can greatly decrease the packet losses that caused by the collision inside LoRa network.

For further improving the energy efficiency, some researchers focus on the improvement across PHY and MAC layers. Focusing on the energy fairness in the network, Gao *et al.* [63] considered the resource allocation problem in multigateway LoRa network scenario. The authors establish a model to evaluate the relationship between network resource and energy fairness, and deploy a greedy algorithm to obtain a suboptimal resource allocation solution. Through energy fairness of the whole network, this scheme avoids that parts of the LoRa nodes in the network run out of their energy too soon. Backscatter systems for LoRa are also considered. Talla *et al.* [64] designed the first LoRa backscatter system. In this system, the LoRa backscatter devices can transmit LoRa packets with a very low energy supply. Talla *et al.* [64] and Peng *et al.* [65] developed an ambient excitation LoRa backscatter system that can achieve low-power and long-range connectivity for IoT devices, and improves energy efficiency of the whole system. In this system, the LoRa backscatter devices can transmit LoRa packets with a very low energy supply. Slabicki *et al.* [66] proposed an adaptive configuration mechanism of LoRa networks, called ADR. The key idea of ADR is that the LoRa servers estimate the link budgets of every LoRa node and according to the link budgets to configure the transmission parameters of each LoRa node adaptively. In this way, ADR can increase both the reliability and the energy efficiency of LoRa communications over a noisy channel.

IV. ENERGY-EFFICIENT COMPUTING IN IIOT

In the IoT network, IoT devices do not just simply transfer data. Most IoT devices need to process the sensing data and may have some computation demand. However, computation is very energy consuming, which obstructs low-power IoT devices to execute complex computation tasks. Moreover, low powered IoT devices are also computationally resource constrained, and can barely satisfy the latency requirements of some tasks. In order to save energy while satisfying latency requirements, one method is that IoT nodes offload their tasks to edge servers or fog nodes or cloud centers by edge computing or fog computing or cloud computing, respectively.

In the edge/fog computing framework, IoT devices can offload tasks to the edge/fog server, where the tasks will be executed and the results will be returned. The energy consumption of communication generally smaller than it of computation. Thus, the energy of nodes can be saved. The energy consumption in such frameworks is mainly related to 1) the energy consumption of executing tasks in local, 2) the energy consumption of transferring task data, and 3) the energy consumption of executing tasks in edge/fog servers. Task-offloading strategies determine not only the three parts of energy consumption but also the task delay. For example, if executing task in local, there are no delay and energy consumption caused by data transmission between the IIoT devices and edge/fog servers. However, this might incur long task execution time and large energy overheads of IIoT devices, because the computational resources on the IIoT devices are usually very limited. If offloading tasks to edge/fog servers, the energy consumption caused by data transmission is introduced while the energy of executing tasks is reduced for

TABLE VII
ENERGY-EFFICIENT MECHANISMS IN EDGE/FOG

Framework	Optimization objective	Restraint	Key solution	Refs
MEC	Energy consumption	Task delay	Energy and time consumption prediction model	[54]
	Time and energy consumption	Computing resource tasks delay	Stackelberg game approach	[55]
SDN+Edge	Energy consumption	Data flow delay	Heuristic algorithm	[56]
	Trade-off between energy efficiency and bandwidth, trade-off between energy efficiency and latency	Energy, bandwidth, latency	Multi-objective evolutionary algorithm based on Tchebycheff decomposition	[57]
Edge+Cloud	Carbon footprints, interference, energy consumption	CPU; memory, bandwidth	Mosek solver	[58]
Fog computing	Energy consumption	Task delay	Accelerated gradient algorithm	[59]
		Task delay, energy consumption		[60]
		Task delay, processing rate, transmit power	Queue models and ADMM-based istributed algorithm	[61]
	Energy consumption, delay, and payment cost	Transmission power, average request arrive rate, computing capability	Queue models and game theory	[62]
	Energy consumption, delay, and weights of mobile devices	Average requests arrival rate transmission power of mobile devices the service rate of fog nodes	Lyapunov optimization	[63]

IIoT devices. As a result, to further improve the energy efficiency of this framework, the task-offloading strategy become a considerable question. There are a lot of researches has been conducted.

Table VII summarizes some of the major works, which consider energy efficiency in edge/fog computing. For mobile edge computing (MEC), Liu *et al.* [69] designed an offloading framework for mobile RFID systems. In this framework, mobile readers are computational resources-limited and energy-constrained, thus, need to offload their computational-intensive tasks to the edge server for saving their energy consumption. The authors model the energy consumption characteristics of different components in such a mobile RFID system, and optimize the energy consumption with the constraints of total execution time. Then, an energy and time consumption prediction model is adopted to solve this problem. Different from [69], [70] optimizes both time and energy consumption simultaneously. Zhang *et al.* [70] proposed a mobility-aware two-layer hierarchical edge computing framework, which consists of a computation layer and a data layer. Specifically, computing servers are powered by renewable energy. Thus, these servers have higher computing energy efficiency. By jointly considering energy consumption and task delay, Zhang *et al.* [70] formulated the green offloading with low latency problem as a concave multiplayer game. Then, the authors use a Stackelberg game approach to solve the problem and find the optimal offloading strategies.

For the cooperation framework of software-defined network (SDN) and edge computing, Li *et al.* [71] focused on the exchange of data with different delay flows among different smart devices, and proposes an incorporation framework of global centralized software-defined network and edge computing to find the optimal routing path for data flow in IIoT, with the deadline, traffic load balances, and energy consumption guaranteeing. Same as [71], [72] is based on the incorporation framework of SDN and edge computing, and aims to find the optimal flow scheduling and routing strategy. In the edge-cloud assistance framework, Kaur *et al.* [73] focused on the container management and schedule on edge-cloud nodes. The authors formulate the problem as an integer linear programming problem based on three objective optimizations: emission of carbon footprints, interference, and energy consumption.

In the fog computing scenario, Chen *et al.* [74] proposed an offloading mechanism, which aims to minimize energy overhead with the constraints of task delay. The authors present an accelerated gradient algorithm to solve the optimization problem, reaching a better convergence speed than traditional schemes. Same as [74], Chen *et al.* [75] adopted the accelerated gradient algorithm as well. However, Chen *et al.* [75] formulated the optimization problem of energy consumption with the constraints of both desired task delay and energy consumption. Chang *et al.* [76] used two queue models to formulate the energy-efficient optimization problem with the objective to minimize the energy consumption and the constraints of tasks' execution delay, fog nodes' processing rate, IoT devices' transmit power. The authors propose an alternating direction method of multipliers (ADMM) based distributed algorithms to generate the offloading strategy. Liu *et al.* [77] presented a theoretical analysis on the energy consumption of computation offloading in a general fog computing system, based on the queuing theory, and then propose an offloading algorithm to jointly minimize the energy consumption and delay. Based on the abovementioned results, Liu *et al.* [77] investigated the impact of social network and energy harvesting (EH) techniques on the design of fog computing IoT network. With the objective to minimize the social group execution cost, a game theoretic computation offloading scheme is proposed for fog computing systems with EH devices. In [78], for minimizing the energy consumption, delay and weights of MDs in the system, the authors present a dynamic computation offloading and resource allocation scheme based on Lyapunov optimization for the IoT fog computing system.

V. OPEN ISSUES AND CHALLENGES

Although a great effort has been dedicated to the energy efficiency of IoT or IIoT system, there are still many open issues and corresponding challenges, due to the stringent requirements of 5G and B5G systems. In addition, the emerging of new technologies such as distributed cloud, blockchain, fog computing, and edge computing also brings opportunities for the further enhancement of energy efficiency in IIoT. In this section, we will highlight some open issues, challenges, and possible research trends.

A. Coexistence of Heterogeneous IIoT Devices

As in the industrial environment, many different sub-IIoT systems will coexist and operate in the vicinity, and they often use heterogeneous hardware and software. Such heterogeneity leads to two critical challenges for the energy efficiency of IIoT.

1) *Interactions among the heterogeneous subsystems.* In most IIoT systems, the interactions among the heterogeneous subsystems are essential. The reason is: 1) the subsystems often need to cooperate in a working flow. 2) The owners and managers require to know a holistic view of the entire IIoT systems, which requires a network of those subsystems.
2) *Interference caused by the heterogeneous subsystems.* Since the subsystems often operate nearly to each other in the manufacturing environment and they are equipped with limited resources, the subsystems can cause severe interference to each other.

Therefore, extra efforts are required to address the above challenges. One possible solution is to exploit the cross technology communication (CTC), which enables the communication between different communication technologies [79]. The direct communications between heterogeneous devices can save many redundant transmissions for the IIoT systems. However, the current CTC designs mainly focus on the data transmission between different PHY-layered devices but do not provide a holistic solution to the IIoT systems. For example, how should we effectively utilize the limited data rate of CTC? Now, a few research works have discussed how the information conveyed by CTC is utilized. We assume they transmit the control or maintenance messages that contain limited information. However, in real-world scenarios, the information exchange among heterogeneous subsystems could be large. As a result, how to employ the CTC to transmit more information is also a trending problem that should be considered in the IIoT energy efficiency.

B. Handling of the Mobility in IIoT

With more and more mobile devices involved in IIoT, such as robots, mobile sensors and unmanned aerial vehicles in industrial automation and monitoring scenarios, the mobility of the IIoT devices becomes an important factor that affects the performance of the entire system.

For large-scale IIoT systems, the duty cycles are often employed to prolong the network lifetime. However, when the network nodes are mobile, the duty cycles will not well properly as the network topology changes. As a result, there is a new tradeoff between energy consumption and the reliability for the energy-efficient mechanisms in mobile IIoT. In order to keep the connectivity of the network, each network node needs to wake up frequently and update the network topology according to the latest wireless measurement. Moreover, the link quality of wireless channels, the routing paths, the network parameters such as transmission powers and coding rates are all affected by the dynamics caused by mobility. Some results of real-world experiments show that the performance of LPWAN is surprisingly susceptible to mobility, even to minor human mobility. The mobility of IoT devices will lead to packet loss, which in turn increases the energy consumption. As a consequence, it is worthwhile to further study, the energy-efficient mechanisms that accommodate the network mobility.

For addressing these issues, possible solutions should be revealing a model among mobility, network parameters, and energy efficiency of the system. Based on the model, lots of lightweight mechanisms could be derived, such as adaptive network protocols, self-tuning network parameters, etc.

C. 5G Enabled IIoT

The emerging 5G technology, with its supporting techniques such as network function virtualization, SDN, and ultradense networks, are capable of offering novel connection and computation paradigms for IIoT systems, bringing new potential in improving the performance of IIoT systems in terms of latency and energy consumption.

When integrating IIoT with the 5G architecture [68], the number of network services requested by the IIoT devices can be extremely large, considering the scale and heterogeneity of the IIoT system. Therefore, the management involving the network services, the IIoT nodes, and the interactions between them becomes one of the key issues in the 5G-IoT paradigm.

1) *Energy-Efficient Network Management.* In the 5G-IIoT paradigm, due to the massive number of IIoT devices involved in the systems, the network will have to maintain a large number of heterogeneous services at the same time. Therefore, service management becomes a key issue. For example, to serve the same number of device requests, the number of service instances can vary in a broad range [67], which means the resource used can also vary drastically. Therefore, we need to further design the service management schemes that are specialized for the IIoT scenarios.

2) *Flexibility and Scalability of 5G-IIoT Network.* Due to the dynamic nature of the IIoT networks, network nodes can join and quit the network at any time. Besides, the mobility of the network nodes can also change the network density dynamically. The changing network density, apparently, will further affect the service quality provided by the 5G network.

As a result, it is essential to ensure the flexibility and scalability of 5G-IIoT network. Possible directions include designing adaptive network adding/removing mechanisms, incremental service orchestration, which tries to reutilize the already allocated network resources.

D. Light-Weight Security and Privacy Assurance

Information security is one of the major concerns for industry management. IIoT systems generate, process, and exchange vast amounts of security-critical and privacy-sensitive data, which makes them attractive targets of attacks. However, Due to the low-cost requirement, IoT devices are often poorly secured and susceptible to become the targets of cyber attacks, such as distributed denial of service or sabotage attacks [80]. Security and privacy assurance become challenging issues. A reliable security protection and privacy assurance mechanism for IIoT needs to meet the following requirements: data and user confidentiality and integrity, user authentication and authorization, service availability, data freshness, nonrepudiation, forward, and backward secrecy ensuring [19].

However, the cryptography algorithms are often very heavy and can incur unacceptable overhead. The heterogeneity of IIoT networks further increases the overheads of IIoT systems. Therefore, it is essential to design lightweight algorithms to ensure the security and privacy in IIoT [46]. The recently proposed framework, federated learning [81], is a good start for privacy-preserving yet lightweight implementations for complex computations. Following the framework, it is also potential to design distributed frameworks to help the front-end devices perform the complex operations required by security services. Another cutting-edge technology that can be used to enhance security and privacy in IIoT is blockchain [19]. The blockchain is a real-time ledger of records that are stored in a distributed, point-to-point manner and are independent of any central authority [80]. The decentralization and high-efficiency advantages of blockchain make it capable of tracking transactions and saving information for decentralized IIoT devices, without worrying about these data being tampered.

E. Edge Intelligence for Energy-Efficient IIoT

In the 5G scenarios, the highly diverse applications of IIoT are usually contradicting with the demand for massive stable connections and ultrareliable transmissions. To meet all these stringent requirements while maintaining a self-sustainable feature, integrating edge computing to the IIoT, and developing energy-efficient mechanisms is of profound importance. As many works have been dedicated to this area, enabling computing at the network edge is emerging. The network edge with powerful computational resources essentially brings the artificial intelligence (AI) closer to the end users. The combination of AI with IoT spawns a new concept called AI of things (AIoT). In AIoT, IIoT keep generating useful data, while AI draws insights from those data. In general, AI fits into an IIoT system in two locations: the center and the edge. Deploying AI at the center of the IIoT networks, such as the cloud, can generate more accurate predictive analytics or models by utilizing the huge amounts of data from the whole IIoT network. Deploying AI at the edge of IIoT networks, such as edge servers or local, can reduce bandwidth and latency while enhancing privacy and security. By organically combining global intelligence with local intelligence, the resulted edge intelligence paradigm, not only can utilize AI techniques to coordinate the heterogeneous resources across different domains for network energy saving, but also can introduce many new functions to the IIoT devices with marginal energy consumption. In a word, the local intelligence enhances global intelligence, while global intelligence conversely impacts the performance of local intelligence such as accuracy and speed.

VI. Conclusion

The promising potential of the emerging IoT inspired the interests from the industry domain in deploying IoT to achieve industrial applications such as automated monitoring, control, and management. However, with the increasing number of involved devices, the resulted IIoT system may consume substantial amounts of energy, which was considered as the bottleneck for preventing its spread. The issues of energy efficiency in IIoT systems were attracted significant attention from both academia and industry. This article presented an overview of the energy efficiency development of IIoT, especially from communication and computation point-of-view. We first introduced the background and key enabling technologies in IIoT. Then, based on the transmission range, the energy-efficient communication technologies are discussed in terms of short-range and long-range IIoT systems. In addition, we also reviewed the energy-efficient offloading schemes in edge/fog computing IIoT systems. Finally, main challenges are highlighted along with potential research directions, in order to shed light towards green and efficient IIoT systems.

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