How Can Heterogeneous Internet of Things Build Our Future: A Survey

Tie Qiu, *Senior Member, IEEE*, Ning Chen, Keqiu Li, *Senior Member, IEEE*,
Mohammed Atiquzzaman, *Senior Member, IEEE*, and Wenbing Zhao, *Senior Member, IEEE*

***Abstract*—Heterogeneous Internet of Things (HetIoT) is an emerging research field that has strong potential to transform both our understanding of fundamental computer science principles and our future living. HetIoT is being employed in increasing number of areas, such as smart home, smart city, intelligent transportation, environmental monitoring, security systems, and advanced manufacturing. Therefore, relaying on strong application fields, HetIoT will be filled in our life and provide a variety of convenient services for our future. The network architectures of IoT are intrinsically heterogeneous, including wireless sensor network, wireless fidelity network, wireless mesh network, mobile communication network, and vehicular network. In each network unit, smart devices utilize appropriate communication methods to integrate digital information and physical objects, which provide users with new exciting applications and services. However, the complexity of application requirements, the heterogeneity of network architectures and communication technologies impose many challenges in developing robust HetIoT applications. This paper proposes a four-layer HetIoT architecture consisting of sensing, networking, cloud computing, and applications. Then, the state of the art in HetIoT research and applications have been discussed. This paper also suggests several potential solutions to address the challenges facing future HetIoT, including self-organizing, big data transmission, privacy protection, data integration and processing in large-scale HetIoT.**

***Index Terms*—Heterogeneous Internet of Things, architectures, network protocols, challenges, applications.**

I. Introduction

BROADLY speaking, IoT is the interconnection of ubiquitous terminal equipment and facilities with unique digital identity, including smart sensors [1], smart devices [2], industrial systems [3], etc. The data from smart devices can be effectively transmitted to their destinations with many communicating tags and often provide specific location information. The objects are monitored and controlled by the central server of IoT. Through various wireless or wired networks, long or short-distance communication to achieve interoperability, IoT adopts appropriate information security mechanisms to provide controllable and personalized real-time online monitoring, security management [4], service functions [5], etc.

In recent years, researchers have designed and developed various hardware and software platforms associated with IoT, which have been widely applied in the areas of both industry and daily life [6]. In these applications, Heterogeneous IoT (HetIoT) has involved various network architectures, including WSN, Wi-Fi, MCN (3G/4G/LTE/5G), WMN, and Vehicular Network. These heterogeneous network units employ RFID, sensors and other smart terminals to get the comprehensive sensing information anytime, anywhere [7]. They can connect to cloud server by Internet or satellites, and reliably transmit urgent events and data in real time to a remote monitoring center for processing [8]. The monitor at the central server intelligently processes and analyzes a large amount of data to achieve the smart control of objects.

With increasing deployment of wireless smart devices, self-organization and survivability of networks have become particularly important. Bone and Cluster [9], Masai [10], Mesh up [11] and other self-organizing architectures can improve the robustness of network [12]. Besides, some researchers proposed various routing protocols to increase network survivability, such as BP [13], ISOS [14], etc. The coexistence of various heterogeneous network units limits channel resource efficiency, which attracts researchers' attention [15], [16]. Some routing protocols can solve the worst case in network congestion [17] and improve the system throughput. The most important function of HetIoT is to get the sensing data from smart terminals which are distributed over different environments, where the devices are difficult to recharge, such as forests, mountains, volcanoes, and other inaccessible places. Therefore, considering the current development of energy technology, energy saving mechanisms in IoT are hot research topics [18]–[20]. With the increasing scale of HetIoT, increasing amount of private and important information is transmitted. In this situation, it becomes urgent to effectively protect these information. Some intrusion detection systems can detect forged or altered information, and some routing attacks [21].

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T. Qiu with the School of Computer Science and Technology, Tianjin University, Tianjin 300350, China, and also with the School of Software, Dalian University of Technology, Dalian 116620, China (e-mail: qiutie@ieee.org)

N. Chen is with the School of Software, Dalian University of Technology, Dalian 116620, China (e-mail: xnchenning@gmail.com).

K. Li is with the School of Computer Science and Technology, Tianjin University, Tianjin 300350, China (e-mail: likeqiu@gmail.com).

M. Atiquzzaman is with the School of Computer Science, University of Oklahoma, Norman, OK 73019 USA (e-mail: atiq@ou.edu).

W. Zhao is with the Department of Electrical and Computer Engineering, Cleveland State University, Cleveland, OH 44115 USA (e-mail: wenbing@ieee.org).

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Besides, many communication safety protocols were proposed to protect private information [22], [23].

With the wide adoption of HetIoT, heterogeneous networks are processing a large amount of time-critical events and data, which inevitably cause congestion problems. The system fails to work in a timely fashion if there is an emergency event, which results in the decreased capacity of emergency response in IoT. Therefore, it is important to optimize the schedule of emergency events to make IoT services achieve the best performance. In addition, other issues bring a serious challenge to researchers and designers. For example, it is an important issue that explores new effective networking model for large-scale heterogeneous IoT in the future. Besides, with lots of smart devices connected, large amount of data are transmitted, and big data phenomenon exists in HetIoT. Big data's integration and seamless transfer in heterogeneous network units are possible future research directions. Researchers contributed to solving urgent problems, such as safety protection, robustness and big data transmission in large-scale IoT.

This survey's goal is dedicated to discussing the heterogeneity and relationship among WSN, Wi-Fi networks, cellular networks, and vehicular networks. Our main contributions are as follows.

- We present a comprehensive survey of the state-of-the-art in HetIoT research and development. In order to help designers and researchers better understand the concept and connotation of HetIoT, we propose a four-layer HetIoT architecture consisting of sensing, networking, cloud computing, and applications.
- Depending on application requirements, we identify key hot HetIoT research issues in industry, precision agriculture, smart homes, intelligent transportation, security community, etc.
- We identify open issues for building future large-scale HetIoT, such as smart hardware design, robustness, topology construction, big data fusion, and security and privacy.

HetIoT will build a smart world for intelligent industry and modern lifestyle in the future. Relaying on broad application areas, HetIoT will be widely integrated into our production and lives. The proposed four-layer architecture can describe succinctly how HetIoT builds our future life. In sensing layer, sensors can sense everything that is existing in cyber physical world, including environmental parameters, human behavior, facility status, emergency events, etc. In networking layer, sensors exchange each other's information and transfer important sensing data to cloud computing layer based on efficient network topologies. Reasonable decision-makings can be made in cloud computing layer through intelligent semantic analysis strategies. People can receive real-time decision-makings that are sent by satellites to make life easier and comfortable in application layer. Many emerging technologies are based on the four-layer architecture, such as virtual reality, precision industry control, smart cities and intelligent transportation, etc. These techniques can provide the convenient and better life for citizens. Therefore, the HetIoT can monitor, serve, protect, and build our future life.

The rest of the paper is organized as follows. In Section II, we investigate and categorize the existing survey papers. In Section III, we introduce our proposed four-layer of HetIoT architecture. We analyze the research in key enabling technologies in HetIoT in Section IV. In Section V, we classify various applications of HetIoT and highlight critical problems in those applications. We stimulate future research, we highlight a number of research challenges and directions for future research in HetIoT in Section VI. Finally, we conclude this survey in Section VII.

II. Existing Surveys for Internet of Things

Many excellent survey papers published in the recent years that focused on IoT security, communications, and applications. These survey papers are categorized as shown in Table I. From these review papers only one [24] of them introduces the DNS and flat DHT technologies about heterogeneous physical entity in IoT and none of the previous works investigates the heterogeneity of IoT. Our paper is the first on the literature that discusses the heterogeneity and relationship among WSN, Wi-Fi networks, cellular networks, and vehicular networks. The objective of this paper is to survey the state-of-the-art in HetIoT, and provide researcher and designers a comprehensive vision for emerging HetIoT, including directions to future research.

These survey papers that were searched from Scopus and Engineering Village database were published in last five years. We present a categorization of these survey papers in Table I. Five review papers from this categorization discuss the security, privacy and defence that related IoT [31]–[35]. With the communication technology progress, many papers that survey IoT have been published in recent five years. Most survey papers focus on WSN [25]–[27], software platforms and hardware items [37]–[39], architectures [47]–[49], and applications of IoT [50]–[52]. Besides, researchers investigate the new technology and issues about IoT that are data fusion and service-oriented framework [40], [41], context awareness techniques [45], [46], cloud computing [43], [44], industrial applications [29], [30], etc.

Among the aforementioned surveys, the heterogeneous physical entity [24] that is related to IoT is reviewed only by one paper. It only covered the compatible heterogeneity technology for heterogeneous objects. However, the rest of the survey articles did not cover any heterogeneity. In this paper, we investigate the heterogeneity among the architectures of IoT. Based on this thorough analysis, we propose four layers to build the future HetIoT and discuss research advances, open issues that combined both innovative research and novel implementations. Besides, applications, future challenges and potential solutions that are related HetIoT are discussed in detail. We believe that this survey article will help researchers and developers focus on the HetIoT and will guide them towards their future research.

III. Future HetIoT Architecture

IoT is a complex system with multiple heterogeneous networks [53]. We propose a four-layer future HetIoT

TABLE I
AREAS OF RESEARCH OF EACH SURVEY ARTICLE FOR INTERNET OF THINGS

Category	**Reference**
Wireless Sensor Network	[25] 2016, [26] 2013, [27] 2013
Machine-to-Machine	[28] 2013
Industrial Internet of Things	[29] 2016, [30] 2014
Security, Privacy and Defence	[31] 2017, [32] 2016, [33] 2015, [34]2014, [35] 2014
Intrusion Detection System	[36] 2017
Software Platforms and Hardware Items	[37] 2017, [38] 2015, [39] 2013
Data fusion and Service-oriented	[40] 2017, [41] 2016
Energy Conserving	[42] 2015
Cloud Computing	[43] 2016, [44] 2016
Context Awareness	[45] 2016, [46] 2014
Architectures	[47] 2017, [48] 2015, [49] 2014
Applications	[50] 2016, [51] 2016, [52] 2015
Heterogeneous Physical Entity	[24] 2014

architecture as shown in Fig. 1, which includes applications layer, cloud computing layer, networking layer, and sensing layer. The heterogeneity and interoperability of the four-layer is better than previously published architectures for IoT. Every layer of four-layer architecture has independent function and scalability. The sensing data collected from various sensors are stored at cloud servers through efficient heterogeneous networking units. The heterogeneous networking units consist of many different network architectures. Due to improvements in hardware design of sensors and optimization of network topology, HetIoT has been applied in daily life and industry. In the rest of this section, we describe the four layers of our proposed HetIoT architecture.

A. Sensing Layer

In the sensing layer of HetIoT architecture, the various sensors provide meaningful sensing data for the cloud server to record and make decisions, such as environmental sensors, color sensors, flame sensors, motion sensors, camera, etc. A large number of sensors are deployed in monitoring area and construct topology in the form of self-organizing and multiple hops, in which the sensing information is transferred. A typical sensor network system includes sensor nodes, sink nodes and management nodes. The sensing data from sensor nodes are transmitted through sink nodes by multi-hop. Users operate the sensor network and release monitoring tasks through management nodes.

Some nodes are more prone to failures due to environment impact and energy depletion, which often causes network topology changes. In the premise of ensuring network coverage and connectivity, the unnecessary wireless communication links need to be removed by energy control and backbone node selection to obtain an efficient network topology for data forwarding. At present, researchers proposed many algorithms and strategies to promote network robustness, such as heuristic algorithm DPSO [1], GRASP mechanism [2], and WCM protocol based on cognitive learning [3].

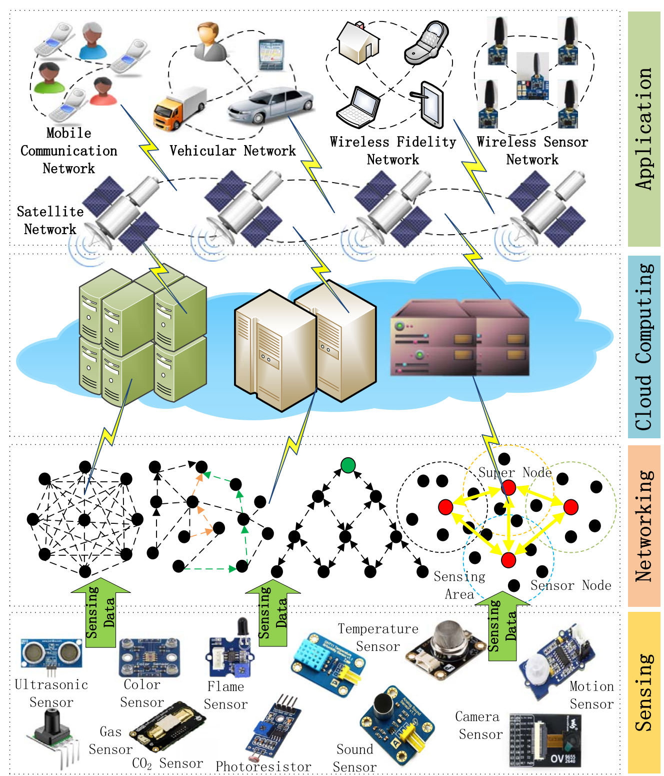

Fig. 1. Future HetIoT Architecture.

In addition, different sensors are existing in future HetIoT architecture, which face the risk of malicious attacks and intrusion. Nodes' location information is one of the safety vulnerabilities, so smart sensor nodes are needed to improve the safe level for HetIoT.

B. Networking Layer

In HetIoT, networking layer is used for constructing an efficient topology to forward data from the source node to destination node. Therefore, networking models are presented to provide high data transmission capacity for nodes, such as star network, tree network, scale-free network, and hybrid network. Besides, these networking models can transmit the data to the cloud server through sink nodes, super nodes, and other relay units. Networking models can also manage the nodes by efficient topology construction mechanisms.

Due to various types of routing protocols existing in HetIoT, networking models have some limitations including energy consumption, data throughput, and malicious attacks. Self-organizing routing protocols improve the robustness of networking models withstand a part of nodes failed. Future HetIoT needs high data transmission capacity to forward the big data to cloud server. To extend the lifetime of HetIoT, energy saving protocols are applied in some harsh environment places without power supply.

C. Cloud Computing

With emerging technology cloud computing, large-scale HetIoT can quickly and accurately handle huge data. Cloud computing layer in future HetIoT will receive and process data from other layers [54]. Cloud servers have powerful analytical computing capacity, and in addition to storing data can also make decisions based on analytical results. In some emergency applications of HetIoT, cloud servers can respond quickly based on emergency event-aware strategies. With increasing level of heterogeneity in the data, smarter decision making using effective cloud computing is required. Compared to middleware, cloud computing has better heterogeneity capacity in IoT because of powerful data analytical feature. Middleware can shield the differences of different operating systems and different network protocols to provide high quality of service for different applications. However, most of the popular middleware services use a proprietary protocol, which is difficult to achieve interoperability. Besides, the middleware services have time delay and memory overhead due to the incompatible protocols of subsystems. Cloud server as an abstract layer can seamlessly realize the communication for heterogeneous systems.

D. Application of HetIoT Architecture

In the applications layer of future HetIoT, there will be many applications, such as MCN, vehicular networks, Wi-Fi, and WSN. People use smart mobile devices to communicate with each other through MCN anytime anywhere, such as WeChat, Skype, Line, etc. Vehicular networks are utilized in intelligent transportation systems to monitor emergency traffic events. People, vehicles, and other smart mobile devices are connected, and vehicular networks can make traffic prediction based on the real time traffic data using the cloud computing layer. Wi-Fi networks can support various network communication protocols and have been widely applied in smart home, smart city, and healthcare systems. People can control the smart devices which connect to Wi-Fi networks.

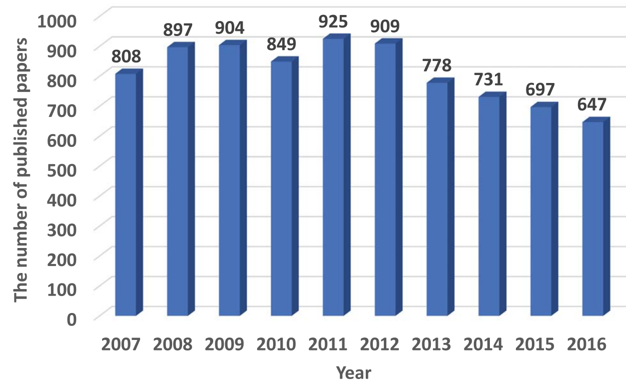

Fig. 2. Self-organizing research in IoT.

WSNs can monitor the environmental parameters, such as temperature, humidity, sound, light, smoke, gas, etc. WSNs have been applied in forest fire detection, debris flow forecast, etc. HetIoT applications are used in our daily life and thus need to provide friendly user interfaces to allow ease of use of the applications. HetIoT employ safe and reliable smart terminal devices which can transfer data to the cloud server layer through satellites. The cloud servers can remotely control the devices based on the analytical data results.

IV. Current Advances of HetIoT

Since IoT concept was put forward, lot of IoT applications have been rapidly developed. With a large number of smart devices connected, the scale of IoT becomes larger, which brings some challenging problems. For example, it is crucial to improve network robustness and survivability in the topology of large-scale HetIoT. Furthermore, data fusion and processing, energy consumption, security issues, and decision making have been the focus of HetIoT research. In rest of this section, we describe the current advances mentioned above.

A. Topology Construction of Networks

Large-scale HetIoT network topology construction is instrumental in connecting millions of wireless smart devices. However, a network topology is easy to change when hardware devices are disconnected. The self-organizing capability is essential to promote network robustness and survivability, and it has attracted intense research interests [55]. The number of research papers on self-organizing architectures and self-organizing protocols from 2007 to 2016 are shown in Fig. 2. The statistical data on self-organizing related research is taken from Engineering Village database. We can see that the published papers are more than 600 per year, and the self-organizing architectures and protocols are the hot research directions. In this part, we will discuss the self-organizing structures and self-organizing protocols for topology construction of HetIoT.

TABLE II
OVERVIEW OF SELF-ORGANIZING ARCHITECTURES

	Advantages	**Disadvantages**
Mesh up [11]	Suitable for mesh networks, universal, high reliability and faster response time	High cost and high energy consumption
Backbone and Clusters [9]	Rapid convergence, efficient stable, strong connection persistent and horizontally extended network size	Small node density and large control overhead
Masai [10]	Large-scale network, better mobility, good performance of bootstrapping	With the data flow increasing, the routing overhead will increase
Engines [56]	Large-scale network, low end to end delay, low energy consumption, better robustness and scalability	Lower throughput
SOWSN [12]	Suitable for large-scale WSN, strong network stability	Lower delay, architectural versatility poor

1) Self-Organizing Architectures: There are various self-organizing structures for different networks in HetIoT. For the next generation radio access network, Ghosh *et al.* [11] proposed the MeshUp architecture based on two mesh topologies GPeterNet, FraNtiC and utilized high-bandwidth optical wireless links to interconnect various network elements. The MeshUp combined with the new wireless backhaul technology has significant advantages in time-delay and network robustness over existing wireless technologies. For mobile networks and hybrid networks, Theoleyre and Valois [9] applied two integrated virtual network structures backbone and clusters to organize network. The backbone optimizes the flooding of control packets and offers a natural extension of wired networks. Clusters provide hierarchical networks, and each layer is logically managed by its cluster head. The self-organizing network with virtual structure has strong robustness and durability properties compared to other methods. Furthermore, a large-scale ad hoc network can be constructed based on a hierarchical architecture. Du *et al.* [10] presented a specific implementation of the Safari architecture for large-scale ad hoc network. Safari provides the routing protocol for scalable ad hoc network and seamless integration of different network infrastructures. Compared to the DSR and L+ routing protocols, Safari can support scalable and decentralized network applications, which have higher data transfer rate and lower packet overhead. Besides, Wakamiya *et al.* [56] presented a 3-layer self-organizing architecture called self-organizing engine. Sirsikar *et al.* [12] presented the SOWSN self-organizing model for distributed nodes in a WSN. The SOWSN gains node behavior with the global and local information to improve the robustness of the network.

In Table II, we provide a comprehensive evaluation of network performance for the above architectures to help the readers better understand the advantages and disadvantages of various architectures. Under the minimum transmission efficiency and energy consumption standards, network robustness is getting better with the development of self-organizing network mechanisms.

2) Self-Organizing Routing Protocols: Self-organizing routing protocols can effectively maintain communication capabilities of large-scale HetIoT. Distributed Hash Table (DHT) as a useful basic framework has been widely applied to self-organizing routing protocols. To improve the self-organizing network scalability, Viana *et al.* [57] discussed a new approach for the distributed and self-organizing system based on DHT routing protocols. They surveyed recent proposals about DHT-based self-organizing systems and combined with significant features to present a discussion about how to construct self-organizing topology in WSN based on DHT.

For the construction of a dynamic self-organizing network, Núñez-Martínez *et al.* [58] presented a self-organized back-pressure routing scheme (BS) based on dynamic Small Cells (SCs) deployments. The SC architecture can reduce the size of a wireless network, which lowers the cost and provides better throughput. The BS aims at reducing network congestion, while having a low routing stretch. When the network is decongested, the BS shows similar performance to the Idealized Shortest Path routing protocol (ISPA), but outperforms the Greedy Perimeter Stateless Routing protocol (GPSR). When the network is severely congested, BS is better than GPSR and ISPA in terms of the average latency. SCs are low-power base stations designed to cope with the anticipated huge traffic growth of mobile communications. Since SCs can not connect with each other, we need low-cost deployment schemes to balance the requirements of backhaul resource consumption.

To tackle the challenges, Núñez-Martínez *et al.* [13] proposed a self-organized back-pressure routing protocol (BP), which was designed to maximize the use of backhaul resources. Through a novel evaluation methodology based on ns-3 emulation, they evaluated BP in the 12 SC indoor tests under different wireless link rates and topologies. Results show Packet Delivery Ratio (PDR) gains up to 50% with respect to shortest path (SP) in terms of throughput and TCP traffic.

In the actual applications of IoT, Ding *et al.* [14] proposed an ISOS self-organizing scheme that built small autonomous regions to balance resources allocation according to self-status and peer exchange. The ISOS scheme can effectively maintain stability across the entire network and has practical significance on the actual network operations. With the development of artificial intelligence, Milner *et al.* [59] proposed efficient self-organizing models and algorithms with artificial intelligence for hierarchical heterogeneous wireless networks (HHWNs). The scheme has good performance with respect to convergence speed and quality of solutions.

In a WSN, efficiency in construction of network self-organizing is low due to bandwidth restrictions, persistent

TABLE III
OVERVIEW OF SELF-ORGANIZING PROTOCOLS

	Advantages	**Disadvantages**
HHWNs [59]	Fast convergence, high stability and intelligence	Small scale and low throughput
ISOS [14]	Easy implement, good stability, balance resources allocation and extend network lifetime	Higher time delay
BP [13]	High speed link connection, strong anti-jamming, higher actual throughput and backhaul link policy scalable	Especially in case of multiple data streams, the end to end delay is longer
BS [58]	Good robustness, low average latency, maintain load-balancing capabilities and overcome gaps between the lower routing extension	Poor network adaptability and lower throughput

energy resources, and other issues. In order to promote the efficiency of WSN self-organizing, Krishnan and Starobinski [60] proposed an efficient clustering algorithm. They simulated many times in different WSN topologies, and the results showed that the algorithm can be extended to a large-scale network. Monti and Moro [61] presented a distributed architecture based on local interactions and devices learning, which is able to self-organize functional data centric sensor networks. The solution scheme can be applied to a variety of networks and has good robustness.

Mobile ad hoc networks (MANETs) are useful for providing network coverage in harsh and adversarial environments, and they can be used in many commercial and military applications where nodes may be randomly or systematically disabled. Gundry *et al.* [62] studied a disruption tolerant topology control mechanism based on differential evolution, called TCM-Y. TCM-Y mechanism outperforms NAC and ADT when nodes and system randomly fail in harsh environments. There are many applications with self-organizing mechanisms in others networks, such as agent networks [63].

As shown in Tables III and IV, we contrast different self-organizing protocols and applications described above. They do not balance data transmission and time delay in topology construction. Therefore, self-organizing mechanisms need to consider cost-effective, transmission rate and delay to achieve optimal network performance with ensuring good robustness.

B. Data Transmission and Processing

We have seen significant research efforts on improving the utilization of limited channel resources [64] and increasing network capacity to address the urgent needs of big data [65]. Efficient data transmission channel allocation strategies have become the focus of HetIoT, especially in WSN, Wi-Fi, MCN, and ad hoc networks. These strategies aim at improving network throughput and transmission speed. Besides, channel allocation and energy consumption are also the hot topics.

A WMN is a "multi-hop" and channel resource-limited network, which results in a low network capacity. To enhance its network capacity and prevent interference of channels, efficient assignment in limited channels has been the focus to optimize network performance. Crichigno *et al.* [66] proposed a scheme that significantly improves throughput and reduces latency while WMN is poor robustness. They presented some solutions that effectively assign channels to optimize network performance in WMN. Besides, there are distributed channel assignment protocols (AO-DV) [67], cooperative channel assignment protocol (CoCA) [15], DPSO-CA [16], etc. These protocols have good performance in network congestion and have better robustness and propagation delay. However, the channel allocation mechanisms in the multi-channel wireless network are often designed without considering adjacent channel interference (ACI) and energy consumption. To prevent such serious interference problems between different users in the network, Uyanik *et al.* [68] proposed DP model aiming at maximizing the spectrum efficiency, specifically trying to minimize the amount of additional guard-bands (GBs) related spectrum. The channel assignment mechanism effectively improves the network capacity.

With the era of big data coming, the amount of data generated by HetIoT is increasing at a very fast rate, which requires the network to have enough bandwidth to meet the customers' needs. Therefore, many protocols, such as TDOCP [69], SIR [70], that maximize network throughput in IoT have been proposed. In addition, Wellons and Xue [17] presented RCART mechanism to ensure that the network performance is the best solution without incurring excessive overhead when big changes happen in network traffic. RCART has significantly solved the worst-case network congestion and improved the system throughput. Except increasing the network capacity in the terms of channel assignment, Fayaz *et al.* [6] presented Ez-Channel, a novel MAC protocol that parsimoniously utilizes the OFDM sub-carriers to perform channelization and assignment of sub-channels to compete for links. The analytical and simulation studies show that Ez-Channel significantly improves network throughput compared with existing protocols that have higher energy consumption.

Li *et al.* [71] proposed a low power data transmission algorithm based on LP. The algorithm can effectively reduce network energy consumption and transmission delay with high throughput, but the network stability is poor. In the WMN, mesh nodes are usually connected to the power supply, and energy saving is achieved by rational channel assignment and efficient routing policy. For example, Avallone [72] proposed a heuristic algorithm and two Mixed Integer Linear Programs (MILPs) that optimally solve the energy consumption of channel assignment and routing problems. The simulation results show that the method has good throughput and energy consumption ratio, but the network robustness is poor.

We sort out the above literature strategies in Table V. Most of the literature focuses on improving the WMN' throughput, but network stability is poor while energy consumption is high. Therefore, in the future, a balance solution for network

TABLE IV
OVERVIEW OF SELF-ORGANIZING APPLICATIONS

	Advantages	**Disadvantages**
WSNs [60]	Efficient clustering algorithm, suitable for large-scale network topology and produce the least clusters	When network is started, the actual time required is longer
Data-Centric Sensor Networks [61]	Using radio operation, low energy consumption, highly scalable and suitable for variety of network environments	High latency and guaranteed minimum throughput
Agent Networks [63]	Efficient data transmission and network scheduling, low energy consumption and low latency	Small network scale and low scalable
MANETs [62]	Suitable for harsh environments, good mobility, high network coverage, good network connectivity and good cost-effectiveness	Smaller scale and larger network delay

TABLE V
STRATEGIES OF CHANNEL ASSIGNMENT

	Suitability	**Throughput**	**Delay**	**Robustness**	**Energy Consumption**
AO-DV [67]	Ad hoc network	High	Low	Low	High
CoCA [15]	WMN	High	Lower	Low	High
DPSO-CA [16]	WMN	High	Lower	High	High
SIR [70]	WMN	Higher	Low	Low	More power supply
TDOCP [69]	WLAN	High	Low	Low	High
MILPs [72]	WMN	Higher	Low	Low	Low
GBs [68]	Wi-Fi	High	High	Low	Low
RCART [17]	WMN	High	High	High	High
Ez-channel [6]	Wi-Fi	High	High	Low	Low
LP [71]	WSN	High	Low	Low	Low

robustness and network throughput can be applied to a variety of networks.

C. Power Supply and Energy Consumption

In order to measure physical values in a physical environment, a large number of sensors are required and they must be densely distributed in the area to be measured. Therefore, rechargeable energy is no longer applicable. Each node needs to reserve energy for long-term use and draw energy from the environment. Power supply problems in smart sensors have been a key issue, which has plagued the development of large-scale HetIoT. The battery maintenance and replacement costs are very large, especially in large-scale WSN. Therefore, reducing the energy consumption of sensors to extend network lifetime and developing efficient energy supply mechanisms will be a hot research topic for the next 5 or 10 years [73]. The statistical data from the Engineering Village database shows that the number of research papers on energy consumption has been increasing since 2007. Nearly 4500 papers on average about energy consumption have been published in recent 5 years. With the development of energy charging technology, researchers have been focusing on the energy consumption which attracts more and more designers and researchers. At present, there are three lines of thought to solve the problem: (1) nodes can save energy to extend lifetime; (2) nodes convert natural environment energy, such as solar power, vibration energy, geothermal, etc., into stored energy; (3) nodes utilize wireless technology to replenish power and manage energy. We review the related research work according to the above classification.

1) Saving Energy to Extend Lifetime: In terms of network energy savings, researchers typically reduce energy consumption through improving communication link status, reasonable using spectrum resources [74], decreasing redundancy, reasonably processing data and data fusion to make information quickly reach the destination node. For example, Patota *et al.* [75] proposed DADNES to reduce power consumption for IP link backbone in network hibernation mode. Different from previous work presented in literature, DADNES can take the switch off decision which neither requires complete knowledge of traffic matrix nor careful tuning of input parameters.

2) Convert Natural Environment Energy: Renewable energy can somehow solve serious energy consumption problems in the wireless network. Han *et al.* [18] focused on energy-aware and quality of service (QoS)-aware load balancing to improve the utilization of renewable energy. Li *et al.* [19] studied energy problems of emergency communications after the disaster, which aims at implementing WMN emergency communications with renewable energy devices.

3) Wireless Technology to Replenish Power and Manage Energy: In wireless rechargeable sensor networks (WRSNs), wireless energy transmission is the best solution to solve the fundamental problem of energy management. Recent research mechanisms are basically based on collaborative wireless charging where each node is allowed to obtain energy from its neighbors. Madhja *et al.* [20] enhanced the collaborative feature by forming a hierarchical charging structure. They stratified the chargers into two groups: the hierarchically lower mobile chargers that charge sensor nodes and the hierarchically higher special chargers that charge the mobile chargers. They defined four new protocols that are either centralized or distributed and assume different levels of network knowledge. The protocols can achieve efficient charging and improve important network properties, such as network lifetime [76], route robustness, coverage, and connectivity.

In future work, the wireless energy transfer will be the mainstream technology trend and lead to a fundamental change of HetIoT. Wireless energy transfer technology can be applied in a large-scale network under harsh environment, which also ensures that the energy consumption of nodes is minimized. The goal of wireless energy transfer is to prolong the network life cycle and to improve the applicability of HetIoT.

D. Privacy and Security Mechanism

Security is an important requirement for sensors when they capture and send sensing data. Research on security mechanisms have been on a rise according to the Engineering Village database. Due to the development of information technology, privacy and public security have received lot of attention in recent years. There are more than 1500 papers published in 2016. Many security strategies are proposed, which have been applied in daily life and production [77]. In the following, we review recent work on HetIoT security issues.

Intrusion Detection Systems (IDS) have been widely applied in HetIoT as an effective defense method. Mitrokotsa and Dimitrakakis [22] discussed the use of the correct classification of intrusion detection in mobile ad hoc networks (MANETs). MANETs play an important role in the computing environment, and provide inexpensive and flexible communication, but it is vulnerable to network layers, such as black hole, gray hole, sleep deprivation and rushing attacks. So far, many schemes and mechanisms have been proposed for secure routing and intrusion detection, such as [23]. Ho *et al.* [78] presented a solution for mobile problems of malicious attack nodes. It can prevent the moving acts of a malicious node through the implementation of all detection locally and preventable acts while maintaining a low-power network state. Raza *et al.* [21] proposed a new intrusion detection system of IoT which detects routing attacks such as forged or altered information, sinkhole, and selective forwarding attacks. Besides, the IDS can be extended to detect other attacks and the system overhead is small enough to be deployed on limited memory capacity and energy constrained nodes. In an intelligent transport system, WMN's intrusion detection mechanism is very important to protect privacy.

HetIoT connects a variety of heterogeneous devices, and all types of communications may be used, even unauthorized networks. Security communication protocols become particularly important to transfer private data between different devices in IoT. MANETs exist in the open wireless communication of mobile nodes. Opponents can start the analysis for the messages embedded in routers and the data packet routing information to detect the communication mode of the system to obtain sensitive information. In response to this attack, Dong *et al.* [79] proposed an anonymous routing protocol that has plurality links. The protocol provides better route request success rate and low delay in all cases compared to other best protocols.

Broadcast transmission is widely employed in HetIoT. Hence, it is key to authenticate broadcast messages. Researchers have proposed many user authentications and key management mechanisms. For example, Grover and Lim [80] classified the current broadcast authentication technologies for designers to select appropriate technology. Turkanović *et al.* [81] applied lightweight key management protocol so that remote users and the general sensor nodes consult the answer key to ensure mutual authentication among the users, the sensor nodes, and gateway nodes. The protocol improves the network properties and security. Besides, Veltri *et al.* [82] proposed a novel centralized approach which can efficiently manage a group key distributed in generic ad hoc networks and IoT. The approach reduces the computational overhead and network traffic due to group membership changes which are caused by users' joins and leaves. The proposed protocol is applied to two following relevant scenarios: (i) secure data aggregation in HetIoT and (ii) Vehicle-to-Vehicle (V2V) communications in Vehicular Ad hoc Networks (VANETs). On the other hand, there are studies that integrate the low-power WSN with Internet security; Granjal *et al.* [33] made a detailed investigation in this respect.

Typically, security is what users are most concerned about. Researchers have done a lot of work focusing on packet detection, protection against malicious nodes, and secure transmission protocols. Security mechanisms must provide effective methods to defend against malicious attacks in HetIoT. But with the development of network technologies, hackers may utilize more than one network technology to attack important nodes. Therefore, ensuring network privacy for a variety of network technologies is the focus of future HetIoT.

E. Sensing and Decision Making

HetIoT and cloud computing are evolving rapidly, and they provide new opportunities for evolutionary design and such tasks as data sensing, collecting, storing, processing and decision making. It is difficult for service oriented IoT to make consensus decisions when sensing data might be insufficient or overloaded. Li *et al.* [83] proposed a cluster-based distributed algorithm. Consensuses are calculated locally, and global consensuses are reached in an iterative fashion. Simulation result shows that this method can improve network robustness and trustiness in the decision process. With the rapid development of emergency response system, HetIoT tends to play an increasing role; the sensors, public services, and experts can interact with each other and make scientific decisions to

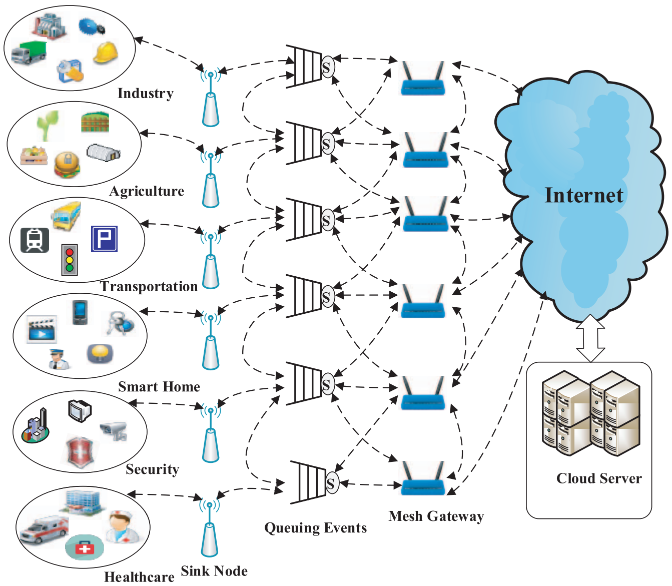

Fig. 3. Applications of IoT.

the emergencies based on real-time data. In a supply chain network system, Li *et al.* [84] divided decision supports of the system into executive layer decision support and tactical layer decision support, which can provide better decision support for enterprises.

Decision making plays an important role in data processing of HetIoT, especially in smart devices that provide personalized recommendations. Researchers pay much attention to decision making from our investigation results. With increasing development of HetIoT, sensing and decision making strategies will be greatly initial in the future.

The future HetIoT will be a complex platform which consists of different topology constructions, routing protocols and data fusion mechanisms. Smarter topology construction is needed to organize the large-scale HetIoT, and stronger sensing and decision-making capacity are needed to serve the HetIoT. These advances introduced above are also the hot focus for the future HetIoT.

V. The Applications of HetIoT

According to domestic and international data since 1999, IoT has been progressing at a fast rate and has penetrated into many industry sectors. It can be predicted that increasing number of industry sectors will embrace HetIoT. In different application fields, there are corresponding network constructions. People can establish social mobile networks based on cellular network, and wireless fidelity networks are usually used indoors. But, wireless mesh networks work in outdoors due to their long distance transmission capacity. As shown in Fig. 3, we classify the applications of HetIoT-based on application scenarios, which include industrial automation, precision agriculture, intelligent transportation, smart home and community safety.

Within the above application scenarios, a variety of devices are connected by intelligent networks, and data collected are transferred to sink node based on queuing priority. The devices connect to the Internet through the gateways, and the remote monitor center can utilize cloud services to analyze data and adopt the corresponding strategy to improve the quality of services. HetIoT has been applied in many fields and promotes the integration of science and technology. In the following, we review HetIoT application based on their area of use.

A. Smart Industrial HetIoT

Various smart devices have been employed in industrial production. In supply chain management, HetIoT applications have been applied to raw materials purchasing, inventory, sale and other areas in enterprises, which improves supply chain efficiency and reduces costs by optimizing the supply chain management system. The sensing and decision-making technology can provide better decision support for enterprises in supply chain network system [84]. In process optimization, HetIoT applications have improved the level of production line process monitoring, real-time parameter acquisition, production equipment monitoring and monitoring of material consumption. For example, Brizzi *et al.* [85] provided an industrial model for production management and maintenance at the manufacturing process. The model also can acquire real-time energy consumption data. In monitoring applications, industrial HetIoT focuses on equipment monitoring and energy management. We can remotely monitor oil and gas stations to ensure safety during operation of equipment. The integration of HetIoT and environmental protection equipment achieves real-time monitoring for various pollution sources. We can utilize new IoT monitoring mechanisms [86] to decrease industrial energy consumption and save resources. In safety production management, sensors have been embedded in mining equipment, oil and gas pipelines, and miners' devices that can sense the safety status information of staff in the hazardous environment. The existing decentralized and independent network monitoring platforms implement real-time perception, accurate identification, fast response and effective control. For example, Rahman *et al.* [86] put forward a number of recommendations in the distribution system for information safety incidents and safety risks to improve the control system that achieves detection capability.

Industry 4.0 can be considered as the foundation for industrial HetIoT. Industry 4.0 integrates industry related technology to create an adaptive, energy-efficient intelligent factory. Shrouf *et al.* [87] proposed a reference architecture based on intelligent factory of HetIoT and defined the characteristics of factories that focus on the sustainable development. They also presented a method based on the intelligent paradigm plant energy management of HetIoT and discussed the expected benefits.

B. Smart Agricultural HetIoT

Agricultural IoT products automatically turn on or off the specified devices in real-time based on sensed data, such as greenhouse temperature, soil conditions, CO_2 concentration, humidity and light signals, leaf humidity, and other environmental parameters. Most of precision agricultural systems are WSNs, and energy consumption is a challenge for sensing area without power supply [75]. Besides, topology construction is another research direction, which can improve the robustness against cyber-attacks. The environmental parameters are captured through WSNs which consist of lots of sensors deployed in monitoring area and constructed in the form of self-organizing and multiple hops. Sensing data are transmitted through WMN or cellular network (i.e., 3G/4G/LTE/5G) to cloud server.

According to users' needs, agricultural HetIoT is ready for processing anytime, automatically monitors agricultural facilities integrated ecological information, automatically controls the environment, and provides the scientific basis for intelligent management to ensure the most suitable growth environment for crops. In real-time monitoring, environmental information is collected by sensor devices inside the greenhouse in real-time, which is transferred to the service management platform through a mobile communication network. The service management platform analyzes and processes the data. Ding *et al.* [88] designed and improved the precision agriculture irrigation system for the sensor network, and the system can detect soil conditions in real-time and provide the ability of independent irrigation.

In remote areas, farmers can log into the agriculture HetIoT production system via mobile phones or personal computers, and control switch valves, exhaust fans, shutters and other devices in the greenhouse, and also can set up the control program that the system can automatically perform according to their circumstances. For example, Sanders and Masri [89] further studied the remote sensing technology that combined with energy management together to achieve a sustainable agriculture. Users need pre-set upper and lower limits in suitable conditions, and the set values can be modified according to the type of crop, growth cycle and seasons. When a parameter limit is exceeded, the system immediately sends a warning message to respective farmers and prompts farmers to take timely measures. For example, Mesas-Carrascosa *et al.* [90] introduced a system that can forecast the production for users, and monitor various environmental parameters that remind the users to take appropriate measures in a timely fashion.

Besides, agricultural HetIoT is also applied to agricultural supply chain manage. With increasing concern about food safety and quality, agricultural suppliers want to be able to track the origin and production process. Duan [91] designed an agricultural supply chain management platform based on IoT by analyzing the information flow's attributes throughout the process of agricultural supply and the technological attributes of IoT. The platform can provide safety of agricultural products for suppliers.

C. Smart Home

Smart home refers to an efficient family matter management system utilizing various technologies such as integrated wiring, network communication, security defense, automatic control, audio, and video. The management system improves home safety, convenience, comfort, artistry and achieves eco-friendly living environment. Smart devices connect with each other by Wi-Fi networks that consist of remote wireless data networks (i.e., 3G/4G/LTE/5G) and short-range wireless connection networks (i.e., Bluetooth, infrared, RFID). Besides, users and smart mobile devices construct cellular network-based social mobile network, and users can remotely control the smart home management system.

Smart home products must address the real needs of users and provide an intuitive user interface. For example, Sim *et al.* [92] applied sound aware technology to detect user behaviors to improve the system's usability. The intelligent subsystems of the smart home should operate round the clock, should attach importance to safety, reliability and fault tolerance of the system.

With respect to power supply and backup systems, the system has taken appropriate measures for various fault-tolerant subsystems to ensure the safety and quality with the ability to deal with complex changes in the environment. For example, Schiefer [93] analyzed the safety threats towards current smart home systems and presented a scheme that classifies the smart home devices based on different levels of security. In standardization, the design of smart home system should be in accordance with relevant national and regions standards to ensure system scalability. TCP/IP should be used to ensure that the system is able to communicate with different manufacturers. Front-end devices for the smart home must be versatile and scalable. Hosts, terminal devices, and modules should adopt standardized interface design to provide an integrated platform for smart home systems and third-party vendors. Systems and products manufactured by different vendors should be made to work with each other.

Compared to an ordinary home, a smart home not only has traditional residential features, but provides a full range of connectivity among buildings, appliances, and automation equipment. New energy saving Wi-Fi direct connection technology has been used in smart homes. Li *et al.* [94] evaluated the power consumption and the downlink interruption performance of smart home systems. Results show that this technology not only improves the smart grid power, but also enhances home reliability. In addition, Liu *et al.* [95] proposed an analysis model that integrated the home smart grid and renewable energy systems, and presented the lowest electricity cost issues, cost-effective power management schemes by analyzing the model. On the other hand, Anvari-Moghaddam *et al.* [96] proposed a smart home energy optimization algorithm, taking into account the balance between the significance of energy saving and comfortable life. The algorithm can not only save resources but also ensure the best comfort of residents.

D. Intelligent Transportation System

Intelligent Transportation System (ITS) is the future for transportation which relies on the Internet of vehicular networks. Due to vehicles' mobility, nodes can leave and join freely on the Internet of vehicular networks. Bluetooth, infrared, and RFID are solutions for fixed and mobile devices to exchange data in vehicular networks. Tacconi *et al.* [97] utilized WSNs to support ITS by effectively integrating advanced information technology and electronic sensor technology in the ground traffic management system. Furthermore, Hsu *et al.* [98] proposed a cloud-based service low-power intelligent transportation system framework that provides reasonable transportation travel guidance by collecting traffic conditions, driving behavior and other related information. The development of ITS has also encouraged widespread adoption of Bluetooth. Friesen and McLeod [99] utilized the existing Bluetooth communication infrastructure and combined it with the short-range communication technology to obtain real-time status information regarding cars, people, and traffic. In addition, the cost-effectiveness of transportation also affects the efficiency of existing transportation facilities. Kolosz and Grant-Muller [100] presented a multiple benefits analysis model that maximally increased operational efficiency with existing transportation facilities when doing so is cost-effective.

ITS is made possible by modern information technologies, which facilitate information collection, processing, dissemination, exchange, and analysis for commuters. Younes and Boukerche [101] proposed an efficient congestion detection protocol that aimed at detecting congested road urban grid layout areas. Furthermore, ITS can utilize a variety of networks to meet the corresponding application requirements. ITS can be effectively used by existing transportation facilities to reduce traffic loads and environmental pollution, to ensure traffic safety and improve transportation efficiency. With the ITS being widely adopted, vehicular ad-hoc networks (VANETs) are emerging as an important technology for ITS. Baiocchi *et al.* [102] proposed a method referred to as TOME, which uses phones to measure VANETs vehicle traffic. TOME can collect real-time information about vehicle traffic and provide accurate estimate in tens of seconds.

E. Security System

By security system, we mean a system both for traditional safety, including anti-theft, anti-robbery, and anti-sabotage, anti-intrusion, and for more generalized security, such as communication safety, fire safety, medical assistance, human protection, anti-gas leak, etc. The security system can effectively monitor internal and external environment by using cameras. The surveillance sites include important sectors, facilities, and public spaces. Such system typically supports image authentication and image recognition. For example, Yuan *et al.* [103] deployed a camera imaging device based on 3D vision technology on the top of cars to monitor vehicles' safety. The security system supports internal probe defense, border protection detection and detection of the critical situation. Duty personnel can receive timely alerts, and take appropriate actions quickly. For example, Sanquist *et al.* [104] designed radiation port monitors (RPM) against human issues for homeland security threat systems. The RPM integrates the radiation spectrum of goods with the signal of commodities data and improves the ability of system detection alarm to reduce the probability of false positives. The central control system includes image recognition control and the control linkage alarm. For example, Gusmeroli *et al.* [105] proposed a right authorization and an advanced access control mechanism. The enterprises and individuals can employ IoT-based security systems to manage their access control procedures to protect their resources and information.

Nowadays, the communities and homes are no longer standalone because HetIoT can interconnect various subsystems so that users can view the situation and receive the advanced warning regarding dangerous and abnormal events at home or on the go. Spanò *et al.* [106] integrated the part of users in smart grid, smart home, and intelligent buildings and presented an IoT platform embedded in these systems. The platform supports various communication protocols to seamlessly integrate various smart home applications, while providing security and custom data access control mechanisms.

F. Smart Healthcare of HetIoT

IoT technology has penetrated into many fields of healthcare [107], ranging from patient vital sign monitoring [108], to rehabilitation exercises monitoring and guidance [109], [110], to individual's daily activity tracking [111] and surgery rooms [112], [113]. Healthcare has promoted the development of wearable smart devices [114], and opened up a new direction of mobile health. Nowadays, smart phones, smart watches, smart bracelets, head mounted smart equipment and other wearable devices detect people's heart rate, blood pressure, sleep state, and activities. These sensing data will provide the wearers with their own health analysis and suggestions for improving their health behaviors [115], [116]. Furthermore, some occult diseases can be predicted. Through medical IoT technology, doctors can remotely check patients' physical condition in real time [117].

Healthcare HetIoT should be people oriented, and smart devices should bring more convenience to patients and doctors, and make surgery safer to patients [112], [113], [118]. Hospital management systems have accelerated the process of digital medical IoT. With analysis result of sensing data from patients, precision medicine will be the future of healthcare. Furthermore, the entire medical industry can be facilitated by IoT and cloud-computing [119].

VI. CHALLENGES AND TRENDS

In this section, we outline future large-scale network technologies and point out important open issues in HetIoT. Fig. 4 demonstrates the theories and key technologies for future HetIoT systems based on our proposed three layers:

(i) *Theory and Modeling:* Future HetIoT will be a large-scale integrated system, which consists of various algorithms and models. So we need improve traditional theories and models to meet large-scale HetIoT systems, such as complex networks, graph theory, queueing theory, and cryptography. According to interdisciplinary analysis, theoretical proofs should be provided.

(ii) *Methodology and Strategy:* Based on above-mentioned theories, we may use greedy principle, optimal path, heterogeneous topology, queueing method, transmission strategy, routing protocols, robustness optimization,

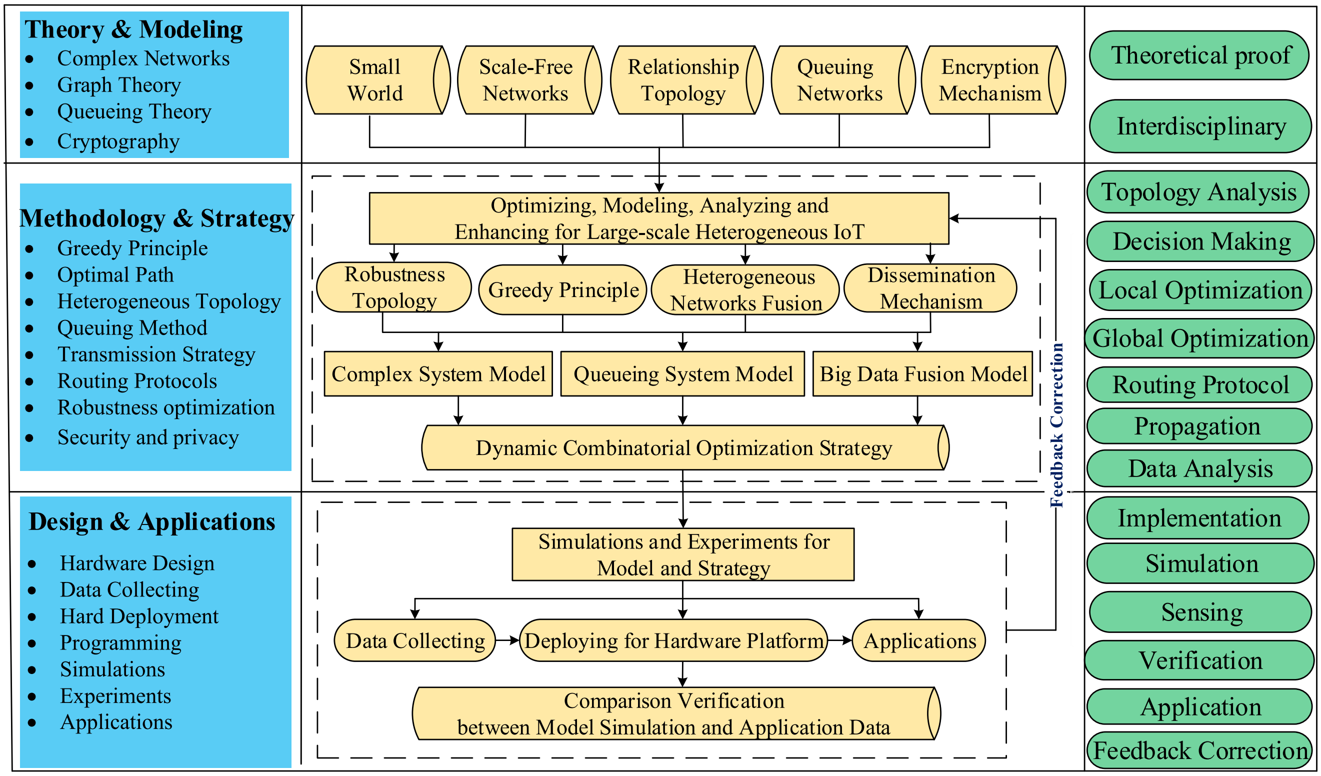

Fig. 4. Theories and Technologies of Future HetIoT.

safety and privacy mechanisms to optimize, model, analyze, and enhance large-scale HetIoT.

(iii) *Design and Applications:* In practice, key technology such as hardware design, data collecting, hard deployment, programming, and simulations are more important. Through simulations and experiments, we can compare results from simulation model and application data. If the theory cannot meet applications, we should perform feedback correction between methodology and design/applications.

A. Heterogeneous Network Architecture for HetIoT

HetIoT is a complex system that consists of many heterogeneous network elements (HNEs). It includes WSN, wireless Wi-Fi, cellular communication network 3G/4G/LTE/5G, WMN and personal LAN and WiMAX networks, etc. The features of these heterogeneous network elements vary widely. Designing a rational heterogeneous topology structure so that all heterogeneous network elements can be coordinated for communication and each heterogeneous network can maximize its efficiency is an important future challenge that researchers need to address [120].

Researchers have proposed applying some traditional modeling methods [121] to guide the networking problems of large-scale HNEs, for example, Queueing Networks, Petri Net, State Machine and Complex Networks etc. These modeling methods can solve the single network architecture issues in HetIoT, and effectively optimize the internal node and network efficiency of a single network element. The single network architecture is a monolithic network with difference networking technologies. However, when HNEs of HetIoT have to work together, these modeling methods have been found to be severely limited. Therefore, how to improve these modeling methods and use appropriate modeling for heterogeneous networks, researchers have conducted explorations to solve the problem in a small-scale modeling of the heterogeneous network environment. But for large-scale heterogeneous networks, it is difficult to find a reasonable solution by applying Queueing Networks, Petri Net, and State Machine modeling methods. Because the Complex Networks modeling method starts by establishing the relationship between networks, it is suitable to build the model for large-scale network topology. In short, for the large-scale HetIoT, exploring new effective topology model is an important issue for the future of the HetIoT technology research.

B. Big Data Integration and Huge Seamless Data Transfer Between HNEs

There are various types HNEs in HetIoT. Data from HNEs must be eventually integrated together. However, network protocols, data transfer interfaces, and configurations of these types of HNEs differ significantly. How these data are integrated or normalized so that data can be transferred seamlessly in different HNEs is a significant issue facing current research.

In most studies of transmission strategies for heterogeneous networks [122], [123], the network scale is relatively small and the number of HNEs is also small. Therefore, researchers normalize different types of data for large-scale HNEs in HetIoT, although the efficiency of the network is significantly affected. When the network size and load reach a certain level, the congestion of HetIoT will happen, even causing a chain-style collapse among networking nodes, which will lead to the paralysis of the entire network. In recent years, Software Defined Networks (SDN) [124], [125] have been proposed to implement different data transfer between HNEs. SDN separates data communication from control layer, which makes network management more centralized and compatible. SDN can enhance virtualization and heterogeneity for HetIoT, but its technology is not mature, and standardization is not high. Even though SDN cannot deal with problems for large-scale HetIoT, it will be an important potential development direction to realize the big data integration and seamless data transfer in the future.

C. Large-Scale Smart Self-Organizing Sensor Networks for HetIoT

HetIoT integrates a large number of distributed ad hoc network nodes that form a network through self-organizing routing protocols and robustness optimization methods [126], and then collaborates on data communication to ensure that data can be sent to the destination node or the control center. When the scale of the network is small, the network load and the number of network links are small, and the transmission efficiency is high. However, the existing self-organizing routing protocols and optimal path strategies are not suitable for large-scale sensor networks whose robustness capacity is poor. Therefore, how to make these large-scale, distributed nodes for efficient self-organizing is a serious challenge to study.

D. Safety and Trustworthiness of HetIoT

Because HetIoT is a complex system that consists of various networks, it is difficult to protect HetIoT internal privacy. Any local information disclosure is likely to lead to the destruction of data privacy globally [127]. For example, if the privacy protection mechanism of WSN is imperfect, the collected confidential data could be stolen or tampered. Therefore, how to design a perfect data privacy protection mechanism for large-scale heterogeneous networks should be one of the future research focuses.

Data privacy protection mechanisms for heterogeneous networks are mainly applied to individual network elements such as Internet, Wi-Fi, WSN and cellular networks. Research is rare on the integration of HNEs. However, the goal of HetIoT research should be to achieve multi-network integration. In order to prevent local data theft or tampering, which would cause global damages to HetIoT, researchers are trying various modeling methods, such as Complex Networks, State Machine, Cryptography and Petri Net, to minimize data damages.

E. Smart Hardware Design for HetIoT

With the increasing development of business HetIoT, lot of hardware networking components have been developed [128], such as wireless fidelity module, RFID module, the infrared module, Bluetooth module, etc. Those hardware components meet challenging demands of applications in data collecting, smart sensing, monitoring, safety, and trustiness. However, the scale of HetIoT increases steadily, and network nodes will face many issues including efficient self-organizing routing, big data collecting, and complex environment monitoring. Thus, a new design for smart hardware components should attract researchers' attentions.

Basically, the traditional network sensor nodes have such characteristics as low-power, limited channel bandwidth, and low computing capacity. But for large-scale HetIoT, sensor nodes need more computing capacity and channel bandwidth to meet the demands of HetIoT applications.

F. Big Data Collecting and Processing of HetIoT

One of the challenges we are facing in large-scale HetIoT is how to process big data timely and effectively, particularly sensing data from different HNEs. We want to ensure the collection and transmission of the data from different HNEs in real-time while ensuring a timely processing of these data. The load capacity of data transmission and processing in various HNEs is different. Thus, on the one hand, balancing the relationship between the each HNE so that real-time data transmission can be effectively guaranteed, needs to be solved for large-scale HetIoT. On the other hand, when massive data have been collected in HetIoT, processing the data efficiently so that HNEs can avoid data generated backlog queue needs to be studied.

VII. Conclusion

Future HetIoT will be based on sensor technology, hybrid networks, cloud computing and storage, and big data analysis to construct smart cities and intelligent sensing. All heterogeneous objects will be independently addressable to achieve interoperability. The functional units of HetIoT can be seamlessly integrated into anywhere anytime, which makes HetIoT adaptable to a variety of scenarios. Furthermore, with the increasing scale of HetIoT, the evolution of HetIoT will be focusing on the communications, smart devices development and intelligent software among heterogeneous network elements to achieve seamless integration of real word and virtual objects. HetIoT thus opens up many new research directions.

In this survey, we first investigated the existing survey papers and presented our proposed four-layer HetIoT architecture where the sensing layer focuses on monitoring sensing data from smart sensor devices. We discussed the typical models in topology deployment at the networking layer. In the cloud computing layer, remote control and decision making have been investigated. Then, we analyzed some classical application fields, such as WeChat, Skype, smart home, intelligent transportation, and safety community in the HetIoT application layer. We also investigated the current research advances in HetIoT. Finally, we highlighted issues and challenges in HetIoT that must be addressed in the future to improve HetIoT. With the increasing number of HetIoT applications, we envisioned that smart self-organizing protocols, big data integration, and huge seamless data transfer will be hot topics in HetIoT research. We hope that this review will be useful for researchers and developers to understand the perspectives, applications, and challenges facing HetIoT. We believe that HetIoT will create a tremendous evolution in the future.

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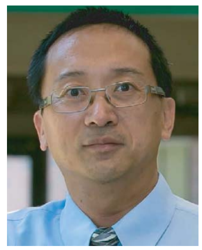
Tie Qiu (M'12–SM'16) received the M.Sc. and Ph.D. degrees in computer science from the Dalian University of Technology in 2005 and 2012, respectively. He is currently a Full Professor with the School of Computer Science and Technology, Tianjin University. He held an Assistant Professor in 2008 and an Associate Professor in 2013 with the School of Software, Dalian University of Technology. He was a Visiting Professor of electrical and computer engineering with Iowa State University, USA, from 2014 to 2015. He serves as an Associate Editor of the IEEE ACCESS JOURNAL, *Computers and Electrical Engineering* (Elsevier), and *Human-Centric Computing and Information Sciences* (Springer), an Editorial Board Member of *Ad Hoc Networks* (Elsevier) and the *International Journal on Ad Hoc Networking Systems*, a Guest Editor of *Future Generation Computer Systems* (Elsevier). He serves as the general chair, the PC chair, the workshop chair, the publicity chair, the publication chair, or a TPC member of a number of conferences. He has authored/co-authored eight books, over 100 scientific papers in international journals and conference proceedings, such as the IEEE/ACM Transactions on Networking, the IEEE TRANSACTIONS ON MOBILE COMPUTING, IEEE COMMUN SURV TUT, TII, the IEEE TRANSACTIONS ON IMAGE PROCESSING, *IEEE Communications*, IEEE SYSTEMS JOURNAL, IEEE INTERNET OF THINGS JOURNAL, and *Computer Networks*. He has contributed to the development of four copyrighted software systems and invented 15 patents. He is a Senior Member of China Computer Federation and ACM.

Ning Chen received the B.E. degree from the Dalian University of Technology (DUT), China, in 2016, where he is currently pursuing the master's degree with the School of Software. He has authored one survey paper in *Ad Hoc Networks* and one scientific paper in the *Journal of Network and Computer Applications*. He is an excellent graduate student of DUT and has been awarded several scholarships in academic excellence and technology innovation, such as National Inspirational Scholarship. His research interests cover embedded system, large-scale Internet of Things, distributed computing, and Internet of Vehicle.

Keqiu Li (SM'12) received the bachelor's and master's degrees from the Department of Applied Mathematics, Dalian University of Technology in 1994 and 1997, respectively, and the Ph.D. degree from the Graduate School of Information Science, Japan Advanced Institute of Science and Technology in 2005. He also has two-year Post-Doctoral experience with the University of Tokyo, Japan. He is currently a Professor with the School of Computer Science and Technology, Tianjin University, China. He has published over 100 technical papers, such as the IEEE TRANSACTIONS ON PARALLEL AND DISTRIBUTED SYSTEMS, ACM TOIT, and ACM TOMCCAP. His research interests include Internet technology, data center networks, cloud computing, and wireless networks. He is an Associate Editor of the IEEE TRANSACTIONS ON PARALLEL AND DISTRIBUTED SYSTEMS and IEEE TRANSACTIONS ON COMPUTERS.

Mohammed Atiquzzaman is currently the Edith Kinney Gaylord Presidential Professor of computer science at the University of Oklahoma. He teaches courses in Data Networks and Computer Architecture. His research interests and publications are in next generation computer networks, wireless and mobile networks, satellite networks, switching and routing, optical communications, and multimedia over networks. Many of his research activities are supported by the National Science Foundation, National Aeronautics and Space Administration, the U.S. Air Force, Honeywell and Cisco He serves as the Editor-in-Chief of the *Journal of Network and Computer Applications* and the *Vehicular Communications* journal and an Associate Editor of the *IEEE Communications Magazine*, the IEEE TRANSACTIONS ON MOBILE COMPUTING, the *International Journal of Communication Systems*, the *International Journal of Sensor Networks*, the *International Journal of Communication Networks and Distributed Systems*, and the *Journal of Real-Time Image Processing*.



Wenbing Zhao (S'99–M'02–SM'14) received the Ph.D. degree in electrical and computer engineering from the University of California, Santa Barbara, in 2002. He is currently a Professor and the Director for the Master of Science in Electrical Engineering program with the Department of Electrical Engineering and Computer Science, Cleveland State University. His current research interests include dependable distributed systems, smart, and connected health. He has over 120 academic publications. He was a recipient of the best paper awards in several international conferences. He is an Associate Editor for the IEEE ACCESS and an Academic Editor for *PeerJ Computer Science*. He has served on the organizing and technical committees of numerous conferences and on the editorial board of several international journals.