Applications of the Internet of Things (IoT) in Smart Logistics: A Comprehensive Survey

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***Abstract*—Logistics is a driver of countries' and firms' competitiveness and plays a vital role in economic growth. However, the current logistics industry still faces high costs and low efficiency. The development of smart logistics brings opportunities to solve these problems. As one of the important technologies of the modern information and communication technology (ICT), the Internet of Things (IoT) can create oceans of data and explore the complex relationships between the transactions represented by these data with the help of various mathematical analysis technologies. These features are helpful to promote the development of smart logistics. In this article, we provide a comprehensive survey on the literature involving IoT technologies applied to smart logistics. First, the related work and background knowledge of smart logistics are introduced. Then, we highlight the enabling technologies for IoT in smart logistics. Furthermore, we review how IoT technologies are applied in the realm of smart logistics from the perspectives of logistics transportation, warehousing, loading/unloading, carrying, distribution processing, distribution, and information processing. Finally, some challenges and future directions are discussed.**

***Index Terms*—Internet of Things (IoT), smart logistics, wireless communication.**

I. Introduction

LOGISTICS plays a vital role in economic growth, and it is a driver of countries' and firms' competitiveness [1]. However, on account of the complex supply chains and high labor costs, the costs of logistics are still at a relatively high level. For example, as one of the high efficient countries in terms of logistics, U.S. spent \$1.64 trillion on logistics in 2018, which is a jump of 11.4% from the prior year and is around 8.0% of the U.S.'s \$20.5 trillion gross domestic product (GDP) according to the Council of Supply Chain Management Professional's 30th annual State of Logistics Report. Whereas, in the least efficient countries, the logistics costs can be as high as 25% of GDP. High logistics costs will affect the efficiency of the manufacturing global value chains and the competitiveness of a country's economy. There is hence no doubt that developing smarter approaches to improve logistics efficiency and reduce logistics costs, in both academia and industry, is a timely and important topic nowadays.

Recently, the concept of *smart logistics* has been proposed [2]–[4]. Smart logistics is based on the modern advanced information and communication technology (ICT). It can realize the modern integrated logistics system in an intelligent way by real-time processing and comprehensively analyzing the information of all aspects of logistics. Smart logistics can bring end-to-end visibility, improve the way of logistics transportation, warehousing, distribution processing, distribution, information services, and so on, and can contribute to time and cost savings. Moreover, it can have the potential to reduce the environmental pollution caused by logistics. However, many challenging issues still need to be addressed in the process of realizing smart logistics. The key issues include how to make it be possible to realize the full interoperability of interconnected devices, how to enable the adaptation and autonomy of smart logistics system to provide it with an always higher degree of smartness.

As one of the important technologies of ICT, the Internet of Things (IoT) is recognized as one of the most important areas of future technologies. Especially, with the rapid development of wireless communication technologies, IoT is rapidly gaining ground in the scenarios of modern wireless telecommunications [5]–[7]. The definition of IoT is constantly evolving from an original focus on machine-to-machine (M2M) connection and applications to the "ubiquitous aggregation" of data. That is, IoT has created oceans of data, the complex relationships between the transactions represented by these data can be explored continuously with the help of various mathematical analysis technologies.

Unquestionably, IoT will play a key role in the implementation of smart logistics [8], [9], which will change the logistics operation mode and the architecture of the logistics system greatly. However, there still are many issues that must be considered during the process of making IoT-based smart logistics be a reality, such as applicable scenarios, existing challenges, and future directions. We conduct this work to help those who are interested in the development and improvement of this domain. Although some surveys related to smart logistics and IoT have already been presented in the literature, they mainly focus on only one of these two areas or one application aspect of IoT in logistics. The purpose of our work is to offer a

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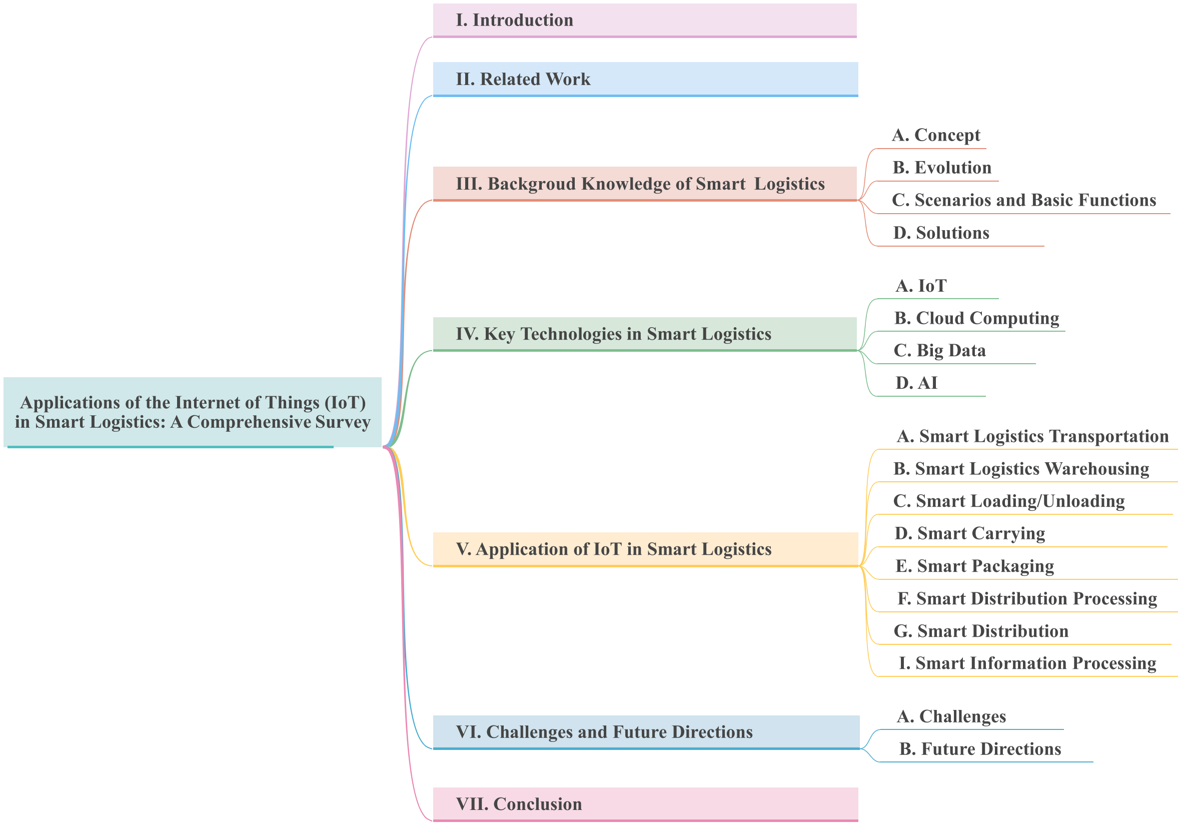


Fig. 1. Roadmap of IoT in smart logistics.

roadmap that considers the related issues in the conjunction of these two areas more comprehensively.

The main contributions of this article are as follows.

1) We investigate the state-of-the-art researches on smart logistics and IoT technologies, summarize and analyze the focuses and inadequacies of different surveys on IoT-based smart logistics and discuss their limits.
2) We present the background knowledge of smart logistics, including its concept, evolution, scenarios and basic functions, and key technologies of smart logistics.
3) We further discuss enabling technologies for IoT in smart logistics, including radio frequency identification (RFID), wireless sensor networks (WSNs), wireless communication technologies, and middleware technology.
4) We highlight the roles of the entities involved in smart logistics transportation, warehousing, loading/unloading, carrying, packaging, distribution processing, distribution, and information processing when integrated with IoT technologies.
5) We discuss the challenges of IoT-based smart logistics in the aspect of data security, data privacy, and resource management. We further present the future work of smart logistics combined with other advanced technologies in the related areas and IoT technologies.

A roadmap of our approach is given in Fig. 1, where we focus on the related work, background knowledge of smart logistics, enabling technologies for IoT in smart logistics, the applications of IoT in smart logistics, challenges, and future direction. We believe that our discussion and exploration will allow readers to understand this field more comprehensively, and promote the related subsequent studies on this issue.

The remainder of this article is structured as follows. Section II presents the related work and highlights our contributions in respect of other existing surveys. In Section III, we introduce the background knowledge of smart logistics. Section IV introduces the enabling technologies for IoT in smart logistics, highlights the latest developments of several wireless communication technologies, and compares their properties. Section V reviews the applications of IoT technologies in the realm of smart logistics. The detailed description is provided from the perspectives of smart logistics transportation, warehousing, loading/unloading, carrying, distribution processing, distribution, and information processing. In Section VI, we discuss the existing challenges of IoT in smart logistics and address the future research directions of smart logistics. In the end, we conclude this article in Section VII.

II. Related Work

There are some surveys about IoT in smart logistics in recent years. Most of them mainly focus on IoT architecture and several application aspects of IoT in smart logistics. Issues of wireless communication technologies, smart logistics development, and challenges are only presented as a small part of these surveys. Unfortunately, as listed in Table I, none of the existing surveys has reported the current situation and challenges of IoT technologies in smart logistics.

TABLE I
COMPARISON OF RELATED WORK ON IOT IN SMART LOGISTICS

Research Content		Related Works	This Tutorial
Backgroud knowledge of smart logistics	Concept	[10] [11]	✓
	Evolution	[10] [11]	✓
	Scenarios and basic functions	[12] [13]	✓
	Key technologies	[12] [14]–[17] [18]–[20]	✓
	Solutions	[12] [13]	✓
Enabling technologies for IoT in smart logistics	RFID	[21] [10] [14] [16] [22]	✓
	WSN	[21] [10] [14]	✓
	Wireless communication technologies	[16] [20] [22]	✓
	Middleware	[21] [14]	✓
Applications of IoT in smart logistics	Smart logistics transportation	[21] [11] [14] [17] [18]	✓
	Smart warehousing	[11] [12] [14]	✓
	Smart loading/unloading	[10]	✓
	Smart carrying	[21]	✓
	Smart packaging	[12]	✓
	Smart distribution processing	[21] [12] [16] [23]	✓
	Smart distribution	[21] [12] [14] [23]	✓
	Smart information processing	[21] [10] [11] [12] [13] [15] [16] [17] [23]	✓
Challenges and future directions	Challenges	[21] [11] [16] [23] [19] [22]	✓
	Future directions	[11] [13] [14] [23] [18] [20]	✓

Ferreira *et al.* [10] reviewed the main technologies of IoT associated with automated support of business processes in logistics. They introduce smart items, including RFID and WSN. Then, they focus on IoT-based support of design and runtime changes considering dynamic changes in business processes. In this survey, IoT is detailed only from smart logistics information processing (e.g., business processes), and wireless communication technologies, other relevant applications, challenges, and future directions of IoT in smart logistics are neglected.

Prasse *et al.* [12] discussed the new requirements and opportunities for cyber–physical logistics systems (CPLSs) that are based on IoT technologies. In this article, they show the concept of CPLS and list the basic technological layers and use a distribution center as a real-world scenario to illustrate the development of CPLS. Although the survey illustrates the detailed solutions of IoT in smart logistics combining with practical application scenarios, it pays no particular attention to challenges of IoT in smart logistics and the impact of new key technologies on smart logistics.

Trappey *et al.* [14] surveyed the literature related to the technologies of IoT that include RFID, WSN, and cloud computing. The construction and the applications of some key technologies of IoT in smart logistics are analyzed by the patent roadmap visualization approach. The authors do not discuss challenge issues and their discussions of future research directions are limited to superficial questions.

Paper [13] introduces the application of IoT in the related fields on the basis of the theories of IoT, analyzes the effect of IoT on logistics information in logistics service supply chain (LSSC), builds the architecture of LSSC based on IoT, and forecasts the application prospect. This survey details the effect of IoT on the logistics information issue, including logistics/service flow, information flow, and fund flow, but no particular attention is paid to applications of IoT in other aspects of smart logistics and challenges.

Lu and Teng [15] analyzed the characteristics of cloud computing and IoT, providing solutions based on cloud computing and IoT to realize logistics information interchange, data exchange. Unfortunately, the authors only focus on the analysis and applications of the key technologies of IoT, neglecting many other important key technologies of IoT and their impact on smart logistics, such as RFID, WSN, and artificial intelligence (AI).

Lee and Lee [16] presented five IoT technologies (RFID, WSNN, cloud computing, etc.) that are essential in the deployment of successful IoT-based products and services. At the same time, the technical and managerial challenges are analyzed. In this article, they introduce IoT-related technologies more comprehensively and discuss the challenges of IoT, but they do not grant adequate attention to wireless communication technologies and the applications of IoT in logistics that are only been mentioned briefly.

In [17], some information processing technologies are used to enhance the design and evaluation of city logistics schemes.

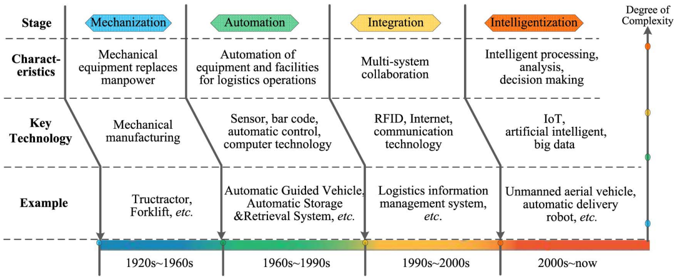


Fig. 2. Evolution of logistics.

Although this article details the applications of information processing technologies and analyzes the effect of the new advanced manufacturing technologies on city logistics, it introduces insufficient detail about the application of new technologies in all aspects of logistics.

Paper [23] introduces the application of IoT in smart logistics in an aspect of logistics distribution and information processing, analyzing the challenges and the future of IoT-based smart logistics. Although the future of IoT-based smart logistics is discussed, the authors only focus on the impact of policy aspects. That means, they do not pay more attention to the impact of the advanced technologies.

Barreto *et al.* [11] presented new challenges in the logistics domain with the emergence of the Industry IoT (IIoT) and address some reflections regarding the most important dimensions required for full implementation of the Logistics 4.0 paradigm. In this article, they propose the concept of smart logistics, introduce the technological applications in the aspect of resource planning, warehouse management, transportation, and information security. Then, they discuss the future direction. Although this article mentions the challenges of IoT in smart logistics, it does not conduct in-depth analysis.

There are other surveys that mainly aim to present the IoT paradigm, such as articles [18]–[22]. In these surveys, different applications of IoT in various fields are introduced, such as domains of transportation, logistics, smart city. Some of those papers discuss the challenges of IoT, including security and privacy. Some discuss the future directions of IoT combining other advanced technologies. For example, Song *et al.* [18] provided the basics and development of smart cities, focused on the foundations and principles needed for advancing the science, engineering, and technology of smart cities, including IoT, and covered applications of smart cities as they relate to smart transportation/connected vehicle (CV) and intelligent transportation systems (ITSs). However, the main limitations of the work are the lack of comprehensive knowledge about smart logistics and wireless communication technologies, especially the applications of IoT technologies in smart logistics are only listed simply.

It is clear that all of the aforementioned articles either do not comprehensively introduce smart logistics, IoT technology, wireless communication technology in IoT, applications of IoT, challenges, and the future of IoT-based smart logistics combining with new advanced technologies or are limited to a part of these issues. In our work, we focus on IoT-based smart logistics and consider the above-mentioned areas. More than offering a classic survey, our intent is to organize the aspects of smart logistics systematically and present a roadmap for applications, challenges, and the future of IoT technologies in these aspects. Compared to other surveys, our version is more convenient and clear for the readers to understand.

III. Background Knowledge of Smart Logistics

Smart logistics is an inevitable trend in the development of modern logistics, the research topic of which has attracted a lot of attention from academia and industry. In this section, we introduce the knowledge about smart logistics briefly from definition, evolution, basic functions, and solutions.

A. Concept

Since "smart logistics" is proposed, there is no consensus on the concept of it has been reached in academia. Fleisch *et al.* [24] proposed the concept of smart products and smart services at first, which means that humans can delegate some of their control activities to smart products and smart services. Smart logistics is defined by Uckelmann [25] based on the concept of smart products and smart services. Uckelmann elaborates on characteristics of smart logistics, which is used to define smart logistics as the given criteria. Barretoa *et al.* [11] defined smart logistics as a logistics system, which can enhance flexibility, the adjustment to the market changes, and will make the company be closer to the customer needs. Cullity [26] presented that the understanding of logistics as the integrated planning, control, realization, and monitoring of all internal and network-wide material, part, and product flows along the complete value-added chain.

With the advanced technologies development, the logistic performance is becoming more and more dependent on technological innovation, the definition of smart logistics has also developed accordingly. As mentioned in [27], smart logistics is often used to refer to different logistics operations (inventory, transport, order management, etc.) that are planned, managed, or controlled in a more intelligent way compared to conventional solutions.

However, no matter how the researchers define the concept of smart logistics, we can find that they have in common that smart logistics combines the advanced information technologies and communication technologies, it can integrate and optimize the logistics system by comprehensive analysis, timely processing, and self-adjustment to make the logistics system smarter.

B. Evolution

The development of logistics is closely related to the advancement of technology. We summarize the evolution of logistics from the perspective of technological development. Fig. 2 shows the evolution of logistics. The development of modern logistics has gone through four stages that are logistics mechanization, logistics automation, logistics integration, and logistics intelligence.

Logistics mechanization can be traced back to the 1920s when the first truck tractor that was used to carry the cargo was built by the CLARK Equipment Company in 1917 [28].

Fig. 3. Smart logistics scenarios, basic functions, and key technologies.

At the first stage, due to the development of the internal combustion engine, mechanical manufacturing, etc., the manpower in logistics activities are replaced by mechanical equipment. With the emergence of sensors, bar code, RFID technology, etc., modern logistics has evolved from mechanization to automation gradually from the 1960s. Representative types of equipment are the automated guided vehicle (AGV) and the automated storage and retrieval systems (AS/RS) and so on. Bozer and Srinivasan [29] introduced an AGV system that is decomposed into nonoverlapping, single-vehicle loops operating in tandem. Hackman *et al.* [30] developed a heuristic procedure to solve the problem that the capacity of the AS/RS was insufficient to store all items. During the 1990s–2000s, logistics evolved from automation to synergy with the development of RFID, network, and communication technology. Gustin *et al.* [31] analyzed the effects of information availability on logistics integration. Alancioni *et al.* [32] discussed how the Internet is being used in managing the major components of supply chains, including transportation, purchasing, customer service, and so on. Paper [33] studies the relationship between information, organizational structure, and the successful implementation of the integrated distribution concept. Leung *et al.* [34] presented a framework for an e-commerce community network, which extends the traditional business-to-business e-commerce to e-commerce at the industry level and realizes the online integration of business transactions. In the 21st century, the rapid development of technologies, for example, IoT, AI, and big data, has promoted the development of smart logistics. Paper [35] investigates a dynamic production logistics synchronization system, which integrates cloud manufacturing and IoT infrastructures systematically to enable a smart production logistics services control mechanism with multilevel dynamic adaptability. Zhang *et al.* [36] proposed a framework depicting the mechanism and methodology of smart production-logistics systems to implement intelligent modeling of key manufacturing resources and investigate self-organizing configuration mechanisms. Paper [37] focuses on the smart connected logistic system, which utilizes all the most advanced principles, such as mobile robotic systems (MRSs), mobile automated platforms, multiagent cloud-based control, and various concepts of IoT. Shin *et al.* [38] proposed a robot control system that can sort parcels automatically with a context-aware mechanism for generating information to control the movement of a robot. The study [39] develops an efficient target-oriented smart integrated multiple tracking system that looks up object location based on real-time and guarantees the accuracy and reliability of logistics location and resource management by combining the function of multiple tracking systems.

C. Scenarios and Basic Functions

Logistics scenarios and the basic functions of smart logistics are shown in Fig. 3. There are eight scenarios in smart logistics, including logistics transportation, warehousing, loading/unloading, carrying, packaging, distribution processing, distribution, and information processing.

1) *Transportation:* Logistics transportation is shipping items from one place to another place using facilities and tools. It is the most important economic activity among the components of logistics systems [40].
2) *Warehousing:* Logistics warehousing is activities that control, classify, and manage the inventory, which is a significant, dynamic element in the logistics supply chain [41].
3) *Loading/Unloading:* It means loading/unloading items at the designated location by human or mechanical means [42].
4) *Carrying:* It is the main logistics operation for moving items horizontally in the same place.
5) *Packaging:* It is to protect products during distribution, to facilitate storage and transportation. It is one of the most important areas of logistics [43].
6) *Distribution Processing:* It means simple operations, such as packaging, division, metering, sorting, labeling, etc., according to the needs of the production place to the use place.
7) *Distribution:* It is a logistics method that delivers the goods to the consignee according to the custom's order requirements. A comprehensive and perfect logistics distribution solution has become an important factor affecting logistics costs [44].
8) *Information Processing:* The dynamic information on production, markets, costs, etc., is collected and processed to make logistics-related forecasts and plans, which enable logistics activities to be carried out more efficiently and smoothly [45].

The basic functions of smart logistics include sensing, integration, intelligent analysis, optimization decision, system support, and timely feedback for each logistics scenario.

1) *Sensing:* It is used to realize smart perception. It uses a variety of advanced technologies to collect a large

amount of accurate information on transportation, warehousing, loading and unloading, information services, and other aspects.

2) *Integration:* It is to achieve data connectivity, openness, and dynamics by the standardization of data and processes. The collected information is transmitted to the data center through the network for data archiving to establish a powerful database.
3) *Intelligent Analysis:* It is to analyze logistics problems using intelligent simulator models and algorithms. During the operation, the logistics system can call the original experience data to do analyze. Then, combining the newly collected data to find loopholes or weak links in the logistics activities.
4) *Optimization Decision:* It is the smart decision function. The smart logistics system can propose the most reasonable and effective solutions by the predictive analysis. Then, it makes more accurate and scientific decisions according to different situations.
5) *System Support:* Smart logistics is not independent of each scenario. Each scenario can be connected with each other to share data and optimize resource allocation, which provides the most powerful system support for all scenarios of logistics.
6) *Automatic Correction:* Based on the previous functions, the smart logistics system can operate following the most effective solution. When some problems are found, they will be fixed automatically.
7) *Timely Feedback:* The smart logistics system is a real-time update system. Feedback is an essential part of implementing system correction and system improvement, which provides a strong guarantee for solving the system problems in time.

D. Solutions

Many researchers discuss smart logistics solutions from the perspective of technology development. For example, Hofmann and Rüsch [46] analyzed the opportunities of Industry 4.0 in the context of logistics management. They present a logistics-oriented Industry 4.0 application model as well as the core components of Industry 4.0 and illustrated potential implications of industry 4.0 on different logistics scenarios. Witkowski [9] discusses some "smart" solutions in logistics and supply chain management according to new technology development of IoT, big data, and Industry 4.0. Barretoa *et al.* [11] illustrated the application of the advanced technologies in the Industry 4.0 era on smart logistics from the aspects of warehousing, intelligent transportation, and information security. Paper [17] describes some applications of big data systems and decision support systems that can be used to enhance the design and evaluation of city logistics schemes.

Some researchers discuss the impact of consumer behavior on smart logistics solutions and propose solutions combining with technology development. For example, McFarlane *et al.* [27] improved the role of the customer in logistics operations and propose a conceptual model for customer orientation in intelligent logistics. Galkin *et al.* [47] examined the influence of consumers on the efficiency of functioning of the logistics system and propose models that allow determining the interaction effects of the logistics system and consumer.

These studies discuss smart logistics solutions from a macro perspective. There are many studies that propose specific logistics solutions for specific logistics application scenarios, which we will describe in detail in Section IV.

IV. Key Technologies in Smart Logistics

As shown in Fig. 3, it needs four key technologies as support to realize smart logistics. That is, IoT, cloud computing, big data, and AI. To provide a picture of the role they will likely play in smart logistics, we introduce these technologies in this section. Furthermore, we highlight IoT and several key enabling technologies of it.

A. IoT

IoT is the basis of the development of smart logistics. The basic idea of IoT [48], [49] is that various objects are able to interact with each other and cooperate with their neighbors to reach the main goal of making a computer sense of information without the aid of human intervention [8], [50] through unique addressing schemes. Using RFID tags, sensors, actuators, mobile phones, etc., the smart logistics system can obtain the information of cargoes, logistics vehicles, transportation routes, warehousing, etc., anytime and anywhere, and can achieve end-to-end information interconnection by network communication technologies. Based on the IoT platform, the smart logistics system can analyze and process massive amounts of logistics data and information, and make a decision to realize smart control of objects combining with cloud computing, big data, AI, and other advanced technologies.

The IoT architecture mainly consists of four layers, that is, sensing layer, network layer, processing layer, and application layer [51], as shown in Fig. 4. The sensing layer is used to collect and sense various physical parameters, logos, audio, video, and other data in the physical world by RFID, camera, 2-D code, and other advanced sensors. The network layer consists of data communication and networking infrastructures for delivering data gathered from devices at the sensing layer to higher layers. The processing layer provides a facility for data access, storage, and processing combining with hardware platforms and intelligent algorithms, such as the cloud platform, big data technology, and AI. The application layer provides access services for IoT users.

In terms of enabling technology of IoT, it needs a lot of technologies, including sensor technology, wireless network, communication technology, and so on. In this part, we focus on several enabling technologies that are widely used for the deployment of successful IoT-based products and services in smart logistics.

1) RFID: RFID plays a very important role in smart logistics to identify and capture the data [52], [53] and it is widely used in various logistics scenarios.

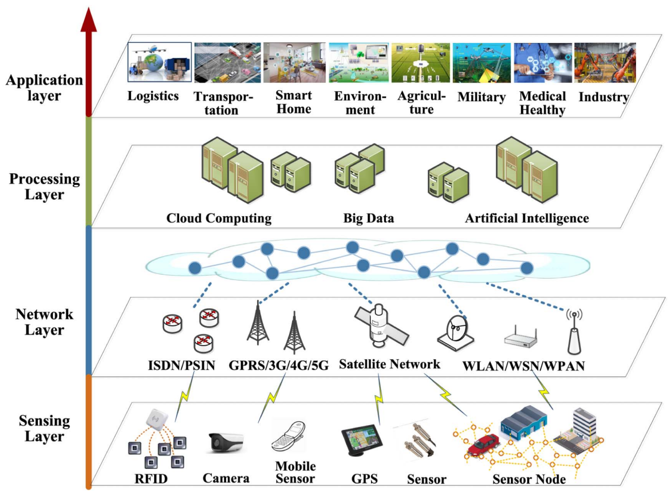


Fig. 4. Architecture of IoT.

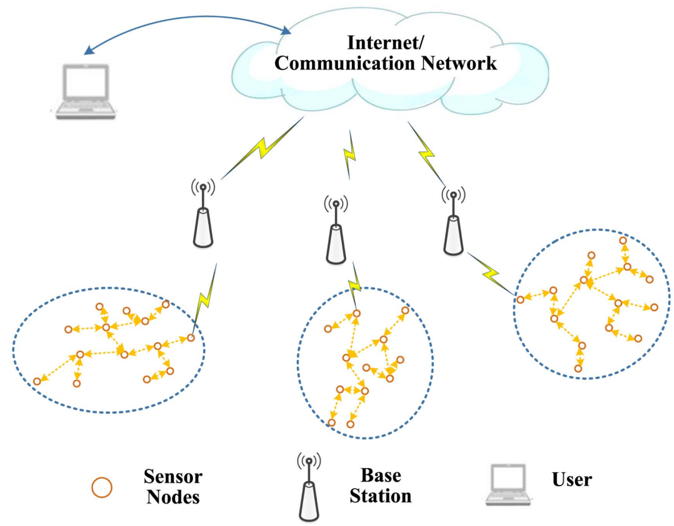


Fig. 5. Architecture of WSN.

It uses electromagnetic fields to automatically identify and track tags attached to objects. Unlike a bar-code, RFID does not need to be within the line of sight of the reader, so it enables identification from a distance. RFID tags support a larger set of unique IDs than bar codes and can incorporate additional data, such as manufacturer, product type, and even measure environmental factors (e.g., temperature) [53].

There are four types of RFID tags according to different frequency ranges, including low-frequency (LF) tags, high-frequency (HF) tags, ultrahigh-frequency (UHF) tags, and ultrawideband (UWB) tags for different application objects in smart logistics (As shown in Table II). For example, the typical applications for LF RFID tags are wares identification and data collection that can be widely used in smart warehousing, smart distribution, and smart packaging [54]–[56]. HF tags can be easily formed into a card shape and are used in electronic tickets, electronic ID cards, etc. [57], so they are common in smart warehousing. UHF tags are mainly used for smart transportation [58], [59], and UWB tags can achieve precise positioning within half a meter, which facilitates the management of valuable instruments and personnel management in smart logistics [52], [60].

2) WSN: Due to a large number of terminal sensor nodes in application scenarios of smart logistics, it is very important to organize and combine these terminal nodes freely. Therefore, WSN has been gained considerable popularity due to their flexibility in solving problems in smart logistics, such as monitoring of transport vehicle status in smart transportation, and item status monitoring in smart warehousing.

WSN [63], [64] refers to a self-organizing network, which is built of tens to thousands of spatially dispersed and dedicated “sensor nodes” for monitoring, recording, and organizing the acquisition data at a central location [65] by wireless connectivity and spontaneous formation of networks. Fig. 5 shows the architecture of WSN.

There are many kinds of network topologies of WSN to organize wireless sensor nodes. According to the node function and the layer of structure, WSN can be divided into a planar network structure, hierarchical network structure, hybrid network structure, and mesh network structure (Fig. 6). Planar network structure [Fig. 6(a)] is the simplest topology in WSN, but its networking algorithm is complex due to the used self-organizing collaborative algorithm. It is usually used in application scenarios with a few network nodes in smart logistics. The hierarchical network structure [Fig. 6(b)] and hybrid network structure [Fig. 6(c)] have good expansibility and are convenient for centralized management, such as inventory, in and out warehouse management, distribution management, etc. The mesh network structure [Fig. 6(d)] is a regular distribution network. The biggest advantage of it is that all nodes have the same computing and communication functions, and there are many routing paths between nodes. Therefore, it has strong fault tolerance and robustness for single point or single link fault, which makes it is a good structure model for building

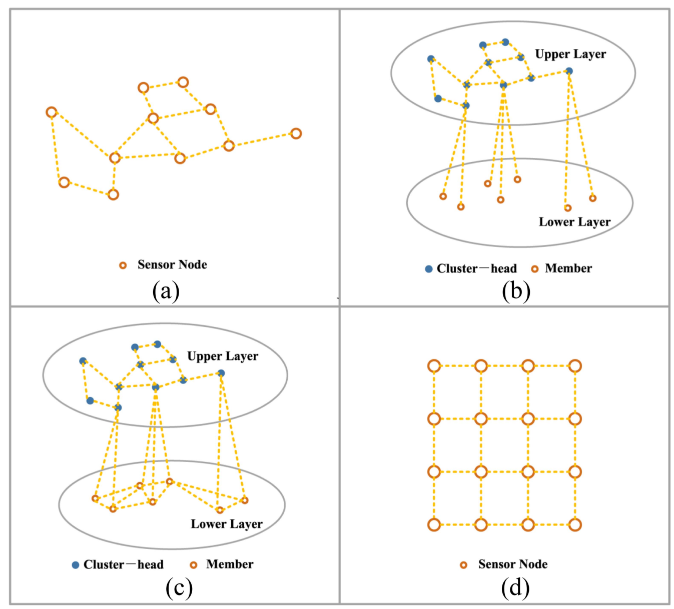


Fig. 6. Network topologies of WSN. (a) Planar network structure. (b) Hierarchical network structure. (c) Hybrid network structure. (d) Mesh network structure.

TABLE II
RFID WITH DIFFERENT FREQUENCY BANDS IN SMART LOGISTICS [61], [62]

Style	Typical Carrier Frequency	Range	Data speed	ISO/IEC	Application scenario
LF	125KHz,133KHz	10cm	Low	ISO/IEC18000-2	Animal identification, factory data collection, car immobilizer, tool identification
HF	13.56MHz	10cm-1m	Low to moderate	ISO/IEC18000-3 ISO/IEC14443 ISO/IEC 15693	Smart cards, electronic ID cards, building access control systems
UHF	865-868MHz (Europe) 902-928MHz (North America)	1-12m	Moderate to high	ISO/IEC18000-6 EPCGlobal	Vehicle monitoring
	2.45-5.8GHz (microwave)	1-2m	High	ISO/IEC18000-4 ISO/IEC18000-5	Toll station, container
UWB	3.1-10GHz (microwave)	Up to 200m	High	Not defined	Valuable instruments and equipment, personnel management

TABLE III
COMPARISON OF SHORT-RANGE WIRELESS COMMUNICATION TECHNOLOGIES IN IOT

	Data Rate	Coverage Range	Power Consumption	Security	Cost	Advantages	Disadvantages
RFID	848Kbps	0.1-200m	10mA	Low	Medium	Quick scan, small size, and diverse shape, reusable, strong penetrability	Higher costs, privacy issue, frequency band consistency issue
Bluetooth	24Mbps	0.5-100m	$<$20mA	High	Low	Low power, low latency, support for complex networks, intelligent connectivity	Short transmission distance, general transmission rate, poor compatibility
Wi-Fi	867Mpbs	10-250m	100mA	Low	High	Wide coverage, high speed, easy to use	Low security, poor stability, high power consumption, poor networking capability, high costs
NFC	106Kbps-424Kbps	$<$0.1m	10mA	Medium	Low	Security, low power consumption, low costs	Close range, slow speed
ZigBee	20Kpbs-250Kbps	10-100m	5mA	High	Low	Low power consumption, low costs, low latency, large network capacity, close range	Weak wall penetration, poor self-organizing ability, and poor anti-interference

large-scale WSN. Therefore, this structure is used in vehicle safety monitoring of smart logistics transportation.

3) Wireless Communication Technologies: Wireless communication technologies are crucial technologies to the field of the network used to collect all sensor node information and send to the base station and the designated client. These technologies enable devices to communicate with others without being physically connected. With the growth of radio-frequency (RF) technology, cellular network, and other advanced technologies, wireless communication technologies keep in stride with an enormous demand for IoT applications in smart logistics.

1) *Short-Range Wireless Communication Technologies:* Short-range wireless communication technologies are very important in smart logistics, such as smart warehousing, smart carrying, smart package, smart distribution processing, etc. In these scenarios, it is necessary to transmit the signals of product status or environment from a few centimeters to several meters. A number of different wireless technologies have been developed for very short distance. In addition to the RFID technology described above, the technologies, including Bluetooth [66]–[68], wireless fidelity (WiFi) [69]–[71], near field communication (NFC) NFC [72]–[74], and ZigBee [75]–[77] are widely used in the field of smart logistics. (Table III). In smart logistics, the corresponding technologies are selected according to the requirements of the application scenario. For example, because of the quick scan, small size, and diverse shape of RFID, it is widely used in various scenarios of smart logistics. The Bluetooth technology is often used in product sorting in smart distribution processing and driver behavior monitoring in smart transportation because of its anti-interference and lower power consumption. NFC can realize various functions, such as electronic payment of vehicles in smart transportation, identity authentication in smart information processing, and anti-counterfeiting in the smart package, etc. For Wi-Fi, it works best for line-of-sight use, so it is often used in smart warehousing, smart carrying, smart package, etc. Although the data rate of ZigBee is not too high, it has a high number of device connectivity that is up to 65 536 that is suitable for warehousing environment data collection, product status information collection, etc.

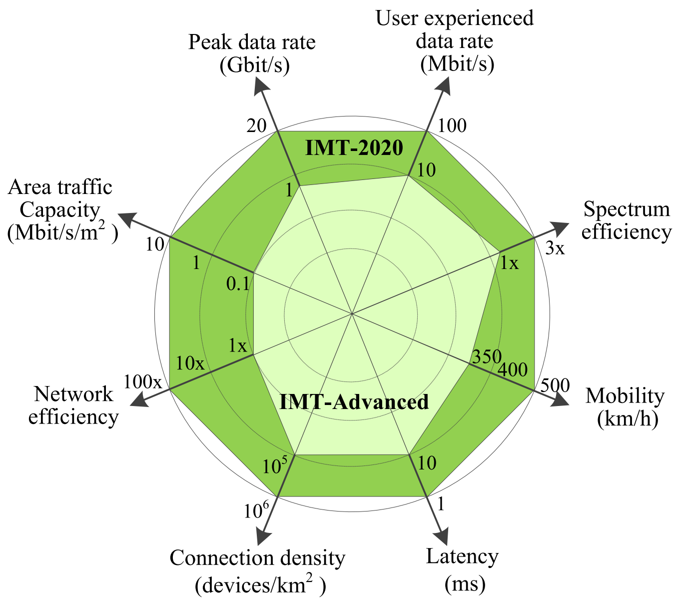


Fig. 7. Enhancements of key capabilities from IMT-Advanced to IMT-2020 [87].

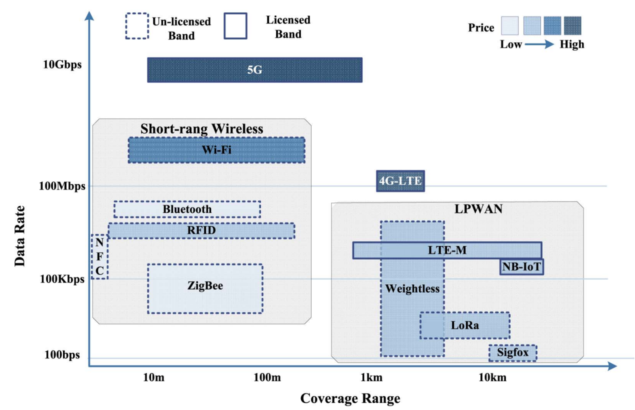


Fig. 8. Comparison of different wireless communication technologies for IoT in smart logistics.

2) *Low-Power Wide-Area Network (LPWAN):* In IoT scenarios of smart logistics, in addition to short-distance communication technologies, long-distance communication technologies are required for wide-range and long-distance connection. At present, the wide-area networks have been built to cover the whole world. However, although the wide-area networks cover a wide range, IoT devices based on these communication technologies have the disadvantage of high power consumption. In order to meet the connection requirements of long distance and low power, LPWAN technologies are designed, which promote the application of IoT in smart logistics. In smart logistics scenarios, narrowband IoT (NB-IoT) [78], LTE-M, LoRaWAN [79], [80], Sigfox [81], [82], and Weightless [83], [84] are getting more and more attention. The main advantages that all LPWAN technologies claim to own are: a) high scalability and coverage range; b) low edge-node energy consumption; c) low costs; and d) convenient roaming network point. Although the data rate of LPWAN technologies is not high, more than 60% of the global IoT market belongs to low-speed business according to the data from McKinsey & Company. Therefore, LPWAN technologies can meet the connection requirements of low data exchange frequency, low connection costs, and a suitable complex environment of IoT in smart logistics.
3) *Mobile Network:* In addition to the above technologies, in long-distance communication, 4G(IMT-Advanced)/5G(IMT-2020) [85], [86] also play an important role in high-speed services of IoT in smart logistics. Especially with the development of 5G, will further promote the development of smart logistics transportation, smart carrying, smart distribution, and so on. Compared with 4G, 5G is a heterogeneous structure, including various frequency bands and communication technologies. The peak data rate of 5G is expected to grow to 20 Gb/s and the latency of it is only 1ms. At the same time, 5G can support devices approximately 1000 times more than 4G in terms of the connected equipment density per square kilometer. Fig. 7 shows the enhancements of key capabilities from 4G to 5G. These performances will greatly promote the applications of 5G in the scenarios, including enhanced mobile broadband (eMBB), massive machine type of communication (mMTC), and ultrareliable and low latency communications (uRLLCs).

To summarize, each of the technologies mentioned above has its own technical advantages and characteristics. Fig. 8 shows the comparison of various technologies in terms of coverage range, data rate, price, etc. In practical applications, appropriate technologies should be selected according to specific application requirements.

4) Middleware: In IoT applications, it is very necessary to have a relatively stable high-level and powerful tool for system integration. Middleware is an independent system software or service program, which can provide a standard data interface to connect the hardware of IoT application and provide data and other resources for system software. Therefore, it plays an increasingly important role in the applications of IoT. It hides the details of different technologies, which is fundamental to free IoT developers from software services that are not directly relevant to the specific IoT application [88], [89]. Most middleware architectures for IoT follow a service-oriented approach in order to support an unknown and dynamic network topology, which means it encapsulates different operating systems to provide an API interface and provides a unified standard interface for the application. In addition, middleware can also provide standard and unified public services to application softwares, so as to shorten the development time and improve the quality of application softwares. Typical middleware in IoT is RFID middleware, sensor network gateway/sensor network node/sensor network security middleware, and another embedded middleware, M2M middleware.

In recent years, the scale of IoT terminal equipment in smart logistics is increasing and the application software is more and more diverse. The connotation of smart logistics information processing is the continuous expansion of various existing applications and the continuous increase of new application forms. For example, in logistics scheduling, it is necessary to integrate information from transportation vehicles, product inventory, distribution personnel, users, and so on. It forces the information processing platform to solve more and more demands, especially the requirements for distributed network applications, such as spanning different hardware platforms, different network environments, the interoperability between different database systems, etc. These requirements can not be met only rely on the traditional system software or Web tool software, therefore, the importance of middleware technology has been increasingly emphasized.

B. Cloud Computing

Logistics system integration is to solve the problem of "information isolated island" in the process of the supply chain. However, the current logistics system is a dynamic, heterogeneous, distributed, and large system. It has the disadvantages of poor dynamic, slow response, low transmissibility, and high maintenance and expansion costs. With the continuous development of smart logistics technology, it is the consensus of the industry to integrate and share the logistics information resources of large systems and provide all kinds of on-demand logistics services for various users in the way of "cloud computing."

Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction [90]. The main objective of cloud computing is to use huge computing and storage resources under concentrated management. Its essential characteristics are as follows: on-demand self-service, broad network access, resource pooling, rapid elasticity, and measured service. Due to its characteristics, cloud computing transparently shares among users scalable elastic resources over a limitless network, which makes it more like the human brain and the nerve center of a smart logistics system.

At present, most of the servers of IoT are deployed in the cloud, providing various services at the application layer through cloud computing. Many researchers have applied cloud computing to smart logistics. Nowicka [91] presents that smart city logistics on the cloud computing model is the concept of citizens' demand-driven flexible logistics infrastructure performance for the sustainable city of the future which is available for any city government interested in sustainable development. Paper [15] introduces a logistics operation based on cloud computing and IoT, which establishes a logistics information interchange, data exchange to meet the business requirements of the various types of logistics public information platform. Arne *et al.* [92] used cloud computing as a hardware platform abstraction for autonomous logistics in order to realize the scalability of the hardware platform. Paper [93] develops and tests a conceptual model for empirically examining the green and costs benefits of integration between cloud service providers and small and medium-sized logistics service providers in the Chinese context. Fig. 9 shows a logistics cloud service mode [94].

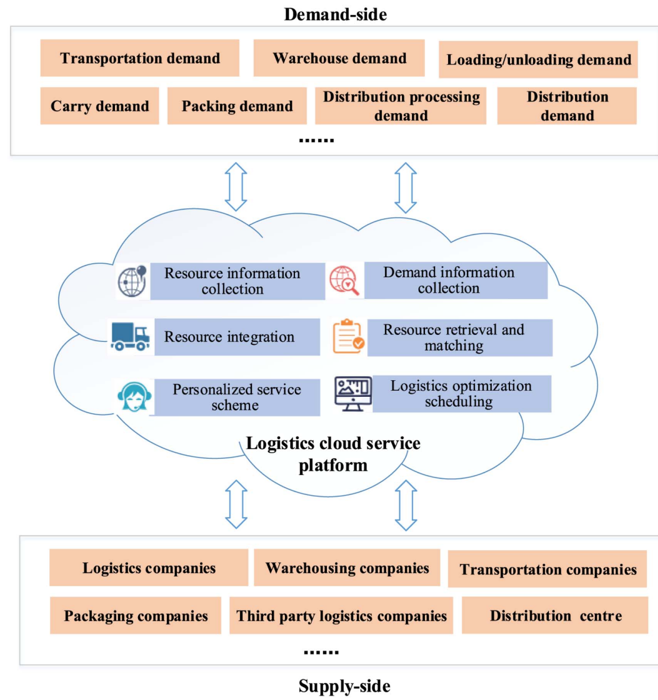


Fig. 9. Logistics cloud service mode.

In short, the application of cloud computing in smart logistics will be more conducive to the integration and sharing of resources, improve the efficiency of logistics operation and service quality, and solve the problems of unreasonable logistics layout.

C. Big Data

As mentioned above, IoT technology can realize the interconnection of things in the logistics system and obtain information from the connected nodes. Cloud computing provides a high-quality technology platform for resource integration. While big data technology can mine new logistics business value through large-scale logistics data collected by IoT combining with cloud computing technology, which will promote the development of smart logistics.

Big data is a technology that treats ways to analyze, systematically extract information from large data sets. These data sets are too large or complex to be dealt with by traditional data-processing application software [95], [96]. Current usage of the term big data tends to refer to the use of predictive analysis, user behavior analysis, or certain other advanced data analysis methods that extract value from data, and seldom to a particular size of data set. Big data can be described by the following characteristics: the big quantity of generated and stored data, the variety of type and nature of the data, real-time data processing velocity, and the high data quality and value [97]–[99].

The significance of big data technology is not to hold huge data, but to extract effective information contained in the data by specialized data processing. It is the basis for the awareness of smart logistics.

There are many studies that apply big data technology to smart logistics. For example, Govindan *et al.* [100] presented

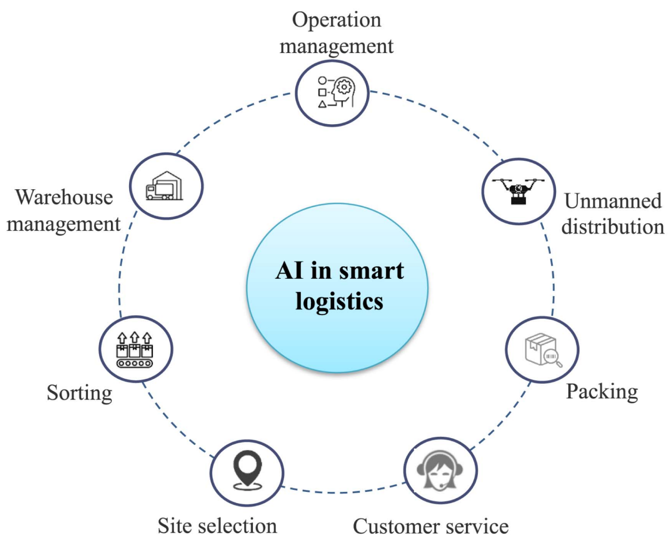


Fig. 10. Fusion scenarios of AI technology in smart logistics.

and analyzed a variety of opportunities to improve big data analysis and applications for logistics and supply chain management. In [101], the authors analyze big data technology in different aspects, which help businesses in the areas of logistics and supply chain. Overall, big data technology has four logistics application scenarios.

1) *Consumption Demand Forecasting:* It can predict the demand of consumers by collecting and analyzing big data, including consumers' consumption characteristics, sales records, purchase platform, and so on, which helps to arrange warehousing and transportation in advance. For example, Amazon analysis customer needs accurately based on big data analysis technology. Through the customer browsing history recorded by the system, the background will put the inventory of customers' interest in the nearest operation center, so as to facilitate customers to place orders. At present, in terms of the prediction accuracy, there is still a lot of room to improve, it needs to expand the amount of data and optimize the algorithm.
2) *Equipment Maintenance Prediction:* Through the real-time acquisition of equipment operation status from the IoT system and big data analysis to achieve premaintenance, so as to increase the service life of the equipment. Ayed *et al.* [102] proposed a novel approach to detect and recognize containers code based on a Hadoop big data analytics system. Volvo's logistics vehicles are equipped with monitoring chips to carry out maintenance in advance through big data analysis. With the application of robots more and more widely in smart warehousing, smart transportation, smart distribution, etc., this will be an important application of big data in the future.
3) *Distribution Network and Route Planning:* Using historical data, timeliness, coverage, and so on to build an analysis model to optimize the layout of warehousing, transportation, and distribution network. Karim *et al.* [103] proposed a logistics trajectories system based on real-time big data analysis, which allows following the movement of products, manage inventories, and optimize stock bearings for materials destined for the production and/or distribution. Wang *et al.* [104] addressed the problem of locating distribution centers in a single-echelon, capacitated distribution network, and presented a distribution network design model with big data.
4) *Supply Chain Risk Prediction:* By collecting and analyzing the abnormal data in the supply chain, it can forecast the potential risks, such as trade risks and goods damage caused by force majeure. For example, in [105], an environmentally sustainable procurement and logistics model is proposed for a supply chain, which provides an optimal sustainable procurement and transportation decision based on big data.

D. AI

AI is an important technology that has a system's ability to correctly interpret external data, to learn from such data, and to use those learning to achieve specific goals and tasks through flexible adaptation [106]. There are three major soft-computing paradigms in AI technology [107], that is, artificial neural networks (ANNs) [108]–[110], fuzzy logic [111]–[113], and evolutionary computation [114], [115]. The application of AI technology will accelerate the development of smart logistics, so it has attracted the attention of researchers as a key technology for smart logistics. Fig. 10 shows the fusion scenarios of AI technology in smart logistics.

1) *Operation Management:* With AI technology, the operation management center will have the ability of self-learning and self-adaptive through machine learning, and can make an independent decision after perceiving business conditions. For example, using machine learning, the logistics scheduling system can learn the command and scheduling experience and gradually realize auxiliary and automatic decision making.
2) *Warehouse Management:* In the future, the unmanned warehouse will be realized by combining AI technology with IoT, big data, cloud computing, etc. It can classify and manage items by an intelligent algorithm. Paper [116] concentrates on automated storage and retrieval using IoT, AI, and cloud computing to have any time access to the stock available in the warehouse.
3) *Unmanned Distribution:* AI is beneficial for transportation. Through the AI algorithm, the unmanned distribution robot can realize path planning, intelligent obstacle avoidance, and so on, which will change the distribution mode and help to reduce logistics costs.
4) *Sorting:* Through the AI system, different cameras and sensors can capture real-time data of millions of goods, and then identify items through brand logos, labels, and 3-D shapes. It means the sorting system no longer needs transport machines, scanning equipment, manual processing equipment, and staff to sort one by one, which will reduce cost greatly.
5) *Packing:* By calculating the volume data and packing box size of products using the AI algorithm, the packing

system can intelligently calculate and recommend packing material and packing sorting, so as to arrange the box type and commodity placement scheme reasonably.

6) *Site Selection:* The location of warehousing and distribution center directly affects the logistics efficiency. AI algorithm can give a location model that is close to the optimal solution by fully learning and optimizing according to various constraints of the real environment, such as the geographical location of customers, suppliers and manufacturers, transportation economy, labor availability, construction cost, taxation system, etc.

7) *Customer Service:* In smart logistics, AI-based speech recognition has become one of the important applications. The customer service agent based on speech recognition technology can realize the visualization and intelligent analysis of the customer's voice, so as to assist the manual agent to quickly search and match the key knowledge points. It will improve work efficiency and service quality. In addition, consumer behavior prediction is also an important part of AI customer service.

In brief, AI will be applied to logistics transportation, warehousing, distribution, management, and so on to achieve an efficient logistics system. Although AI technology is still not fully mature at present, the development of smart logistics cannot be without it. It will lead the future development direction of smart logistics.

V. Applications of IoT in Smart Logistics

In this section, we focus on the applications of IoT technologies in smart logistics from the perspective of wireless communication.

A. Smart Logistics Transportation

In the smart logistics transportation, IoT technologies are often used to complete the real-time monitoring of vehicles, cargo, and driver. During the logistics transportation process, information of the vehicle, cargo, driver situation, etc., are efficiently combined to improve transportation efficiency, reduce transportation costs, reduce cargo loss, and clearly understand everything in the logistics transportation process.

1) Vehicle Status Monitoring: For vehicle monitoring, it mainly includes location tracking and real-time situation of vehicles, such as the speed of the transport vehicle, the tire pressure, the fuel consumption, the number of brakes, and so on.

In [117], a vehicle tracking system is designed and implemented for tracking the movement of any equipped vehicle from any location at any time. The system integrates technologies, such as global positioning system (GPS) and global system for mobile communication/ general packet radio service (GSM/GPRS) technology, in which GPS module is used to get geographic coordinates at regular time intervals and the GSM/GPRS module is used to transmit and update the vehicle location to a database. At the same time, the smartphone application is also developed for continuously monitoring the vehicle location. In [118], an accurate vehicle location system using RFID technology is proposed, which combines with GPS and GSM technology. In this project, an RFID transponder is designed and a read range of approximately 31cm is obtained in the LF communication range (125–134 kHz). Using this system, autonomous vehicle tracking can be facilitated with the use of RFID technology where GPS signals are nonexistent. Feng *et al.* [119] proposed an architecture of the vehicle traffic congestion controlling and monitoring system in IoT. It uses Bluetooth technology to transmit the current status and density of traffic and gets the dynamic traffic conditions by effective data analysis. In [120], the innovation path of logistics formats based on 5G is proposed. This article establishes an intelligent logistics traceability system through the integration of 5G, IoT, and AI, which realizes fully automated transportation and accelerates the development of smart logistics.

2) Cargo Status Monitoring: By cargo monitoring, the location and the status of cargo can be obtained in real time.

An intelligent cargo tracking system based on IoT is proposed in [121]. This cargo tracking system uses RFID, GIS, 3G communication, middleware technology, and AI technology. It realizes cargo tracking through real-time signal acquisition, data communication, and information processing. In [122], dynamic road transport of the dangerous goods monitoring system is proposed, which is based on IoT and RFID technology. This system cooperates with the highway infrastructure and information sharing system databases by cellular communication and gets more information about dangerous goods by information processing. An intelligent cargo solution EURIDICE is presented in [123]. The solution adopts an IoT approach in distributing intelligence on mobile and distributed devices. It allows them to communicate with each other as well as with a central platform. In this manner, EURIDICE provides a number of services, including cargo localization, rerouting, and monitoring of cargo conditions, to be performed without human intervention.

3) Driver Monitoring: In terms of driver monitoring, it can be realized by detecting the driver's healthy and driving behaviors through IoT technology.

Paper [124] describes the wearable sensor network design for a low-power healthcare real-time processing and other application of IoT, which uses the wireless technology to transmit the physiological parameter of the people at remote locations. This design is useful for the driver's community to take some preventive measures and thus road accidents can be reduced to some extends. In [125], an architecture for driver behavior monitoring based on IoT and fog computing is presented. In this architecture, all the environmental, vehicle, and driver influential factors are considered by using multisensors. Data communication can be realized through various communication technologies depending on the different types of sensors and data frequency, such as RFID, Bluetooth, WiFi, or 4G-LTE, and so on. At the same time, to cope with the time sensitivity of data communication, fog computing is used. By applying the above technologies, this architecture can realize real-time monitoring and analysis of driver behavior. Boja *et al.* [126] proposed an architecture for driver behavior analysis by collecting raw data from connected cars in an IoT environment. The system uses mobile technologies in embedded devices and smartphones, and data mining services in Cloud. An assessment solution of driving style is presented in [127]. The solution is designed based on the embedded system designed according to IoT, which can assess the driving style according to the vehicle's speed, acceleration, jerk, engine rotational speed, and driving time.

In addition to the above aspects, in recent years, with the rapid development of intelligent transportation, IoT-based ITSs have gradually been applied to logistics transportation [40], [128], [129].

As mentioned above, in smart logistics transportation, it is necessary for an IoT monitoring system that can collect status information by multisensor and preprocess it in the local embedded system. At the same time, it also needs to establish an interconnection with the logistics center to transmit the status information for further analysis and prediction so as to make a correct scheduling decision. As far as the monitored objects are concerned, vehicles, cargos, and drivers all have the characteristics of dynamic movement. Therefore, the real-time and stability requirements of information transmission are relatively high, which means that the transmission rate and dynamic stability of wireless communication are the primary factors to be considered in the IoT system applied in smart logistics transportation.

B. Smart Warehousing

Warehousing management is becoming more complex and critical as business and technology continue to change. Now with IoT technologies, we can optimize the utilization of warehouse space, monitor the warehouse environment, and improve the product management process.

1) Warehouse Space Optimization: In terms of warehouse space optimization, it mainly includes product location planning and warehouse space structure optimization.

Trab *et al.* [130] proposed a multiagent architecture for product allocation planning with compatibility constraints, which uses a decision mechanism for product's placement, based on negotiations between agents associated to compatibility tests. This negotiation mechanism relies on an IoT infrastructure and multiagent systems are defined in order to solve the security problem of product allocation operations.

In recent years, the most representative application of the warehouse space structure optimization is the AS/RS. Paper [131] introduces the basic concepts of dense storage technology, which includes the mode, scheme, and technical equipments. It studies how dense storage technology can optimize the use of the distribution center concluding combined with an example of the practical application. Ma [132] studied and puts forward a design scheme of an automatic logistics control system for AS/RS based on ZigBee wireless network technology, which adopts the star control structure. This scheme can meet the flexible control requirements of the users and makes a 3-D warehouse logistics control system more intelligent, simple, and effective to improve operational effectiveness. Paper [133] presents an AS/RS system based on a cartesian robot for the liquid food industry, which provides

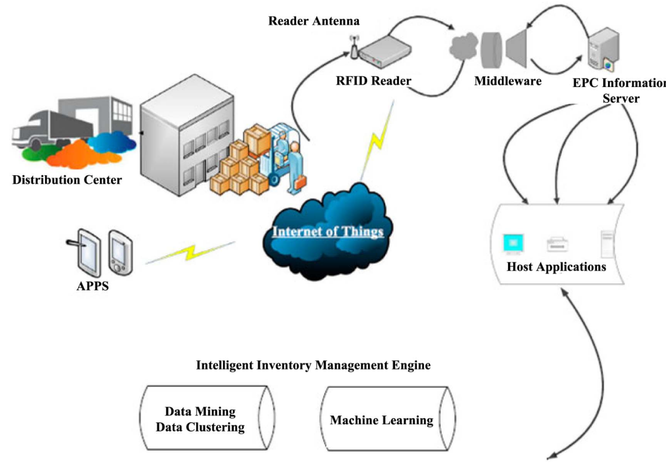


Fig. 11. Framework of the proposed IoT-based warehouse management system [138].

more efficient use of the storage capacity and a more effective control strategy.

2) Warehouse Environment Monitoring: Monitoring warehouse environment mainly includes environment temperature and humidity, power distribution management, etc.

Paper [134] designs an intelligent warehouse measure and control system based on ZigBee WSN and network nodes. In this design, the ZigBee technology is used in warehouse control and environmental management. It can improve the intelligent level of logistics warehousing technology. In [135], an IoT architecture that is suitable for cotton storage is constructed. It uses IoT technologies to improve cotton warehousing management. Yu *et al.* [136] designed an automated warehouse monitoring system based on IoT to solve the problems of the monitoring lagging and nonintelligent. The design can be used to monitor the temperature, humidity, and the case of fire in the warehouse. Chihana *et al.* [137] proposed and developed a novel method that used sensors, wireless radio communication module, and GSM/GPRS technologies. It can be used to sense real-time warehouse intrusion and grain tracking theft so that the human resources needed for grain management can be reduced.

3) Warehouse Management: As one of the warehousing management systems, improving the warehousing management process is very important.

Lee *et al.* [138] proposed an IoT-based warehouse management system with an advanced data analytical approach using computational intelligence techniques to enable smart logistics for Industry 4.0. Fig. 11 shows the typical framework of an IoT-based warehouse management system. Paper [139] combines vehicle tracking and warehouse management to realize warehouse working procedures seamlessly. It adopts a location-based service trigger to manage warehouse procedures. In [140], an RFID-based intelligent warehouse management system is proposed. It makes full use of the existing types of equipment and facilities based on IoT technologies to help to achieve better inventory control, as well as to improve operational efficiency. Jing and Tang [141] proposed the specific framework programs and function modules of an intelligent inventory management system based on IoT technologies.

Combined with the enterprise resource planning (ERP) system, this system can realize full control and management of all products, faster in/out warehousing, and dynamic inventory.

To summarize, the warehouse has the characteristics of fixed location and limited scope, which makes the design process of the IoT-based smart logistics system can be completed according to the characteristics of warehouse structure and environment. With regard to the current research and application status, the wireless communication of smart warehouse is mainly based on short-range communication technology. In the warehouse space optimization system and warehouse environment monitoring system, the network capacity of wireless communication is required to be large, and yet the transmission rate is required to be relatively low. Therefore, ZigBee is very popular in these application scenarios. Warehouse management involves products in and out, and it needs to complete the reading of product information in this process, so RFID is widely used in this scenario. With the development of information integration, mobile network and LPWAN communication technologies are gradually applied to IoT-based smart warehouse system.

C. Smart Loading/Unloading

The basic actions of loading/unloading activities include loading (ship), unloading (ship), stacking, storage, outbound transportation, etc., which mainly refer to the handling on the vertical direction. They are the necessary activities arising from transportation and storage activities.

In the logistics process, loading/unloading activities are constantly appearing and repeating, so they often become the keys to determine the logistics speed and costs. Furthermore, the use of loading/unloading equipments (such as a forklift) based on IoT can greatly improved logistics efficiency. At present, the applications of IoT technologies in this area mainly focus on the following aspects: equipment automation, equipment positioning, equipment status monitoring, equipment dispatching, and so on.

1) Equipment Automation: The automation of loading/unloading equipment is closely linked to logistics costs and efficiency, so there is a lot of research on this.

In [142], a data collection unit (DCU) is designed, which can easily connect several sensors with different interfaces like a controller area network (CAN) port, UART, RS232, and so on. It is applied to the smart forklift that has several sensor modules, such as scale, RFID reader, etc. So that the forklift can get its exact position and eventually deliver the goods in an indoor warehouse instead of people. An IoT-based forklift robot is presented in [143]. The system uses multisensor, including camera, line sensor, sharp sensor, and so on. At the same time, Wi-Fi communication module is used to establish the remote bridge between robot and warehouse operator so as to connect the robot to the Internet and command the robot. Paper [144] describes a client/server application developed for the automation of a fleet of industrial forklifts. In this application, a forklift is completely automated using external an internal sensor and data communication between forklift and server is realized by wireless communication technology. As a result, the application can realize client/server teleoperation and data monitoring. In [145], a mini forklift robot is designed, which can store and pick up an object to/from a specified storage slot from/to a base using line follower and RFID.

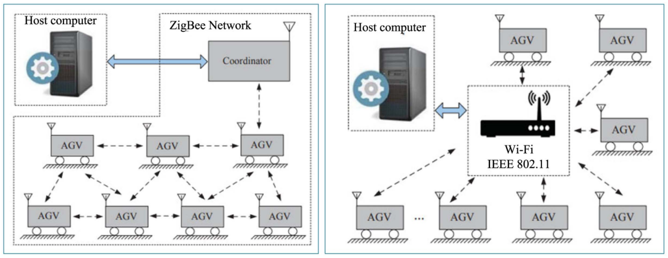
2) Equipment Monitoring and Dispatching: Equipment monitoring includes getting equipment position and monitoring equipment status. Based on this, the equipment dispatching can be realized.

Papers [146] describe a multimodal framework for interacting with an autonomous robotic forklift. The human supervisor can interact with the forklift using speech and sketch by a wireless or handheld tablet. That means, the interface of the system supports commands that include summoning the forklift and directing it to lift, transport, and place loads of palletized cargo through a simpler set of sketched gestures. In [147], a high-performance 5.8-GHz wireless forklift positioning system is introduced. In this system, an optimized heuristic localization method is used to derive the position and orientation of the forklift. The proposed RTOF system concept allows a minimal complexity of the infrastructure since no backbone network and no dedicated synchronization scheme is needed. Hoefinghoff *et al.* [148] made a comparison between measured and simulated field distribution for a UHF RFID system mounted on a forklift truck, by which it can achieve the optimal tag identification positions for reliable communication between the reader and the tag. Estanjini *et al.* [149] proposed an optimizing warehouse forklift dispatching using a WSN and stochastic learning, which is a successful deployment of an inexpensive mobile WSN in a commercial warehouse served by a fleet of forklifts. The system establishes a sensor network platform, which provides enough bandwidth and a reliable transmission protocol to meet the requirement of real-time monitoring. By monitoring the running state of the forklift, including the used time, battery power, location, collision detection, etc., the optimal dispatching of the forklift is achieved combined with the corresponding dispatching method.

For the application of loading and unloading, the current IoT system mainly aims at the realization of loading/unloading automation, equipment status monitoring, and dispatching. From the perspective of communication, because the loading/unloading equipment operates in a certain range, the IoT system mainly adopts short distance communication, such as RFID, WiFi, etc. Only in equipment dispatching, it needs remote information transmission, so mobile communication technology is usually used.

D. Smart Carrying

Carrying is the activities required for the transportation and storage of goods, which mainly refers to the handling of the horizontal direction. In recent years, the intelligent development of carrying is mainly reflected in the development and application of AGV that is used for the internal and external transport of materials [145]. With the rapid development of IoT technologies, the networks based on wireless communication technologies are increasingly applied in AGVs, which usually provide a number of advantages to AGVs, such as low costs and high efficiency [150].



(a) (b)

Fig. 12. Wireless communications of AGVs based on ZigBee and WLAN network [150]. (a) ZigBee. (b) Wi-Fi.

1) Carrying Based on RFID: Among these wireless communication technologies, RFID is the most commonly used.

Lu *et al.* [151] presented an RFID-enabled positioning system in AGV for a smart factory. By examining the key impact factors on AGV's accuracy, such as a magnetic field in circular antenna, circular magnetic field, and circular contours stability, the system can determine the antenna type for different occasions. This can be used to deploy RFID devices systematic in automatic logistics shop. In [152], an AGV wireless control system based on WSN and mobile robot control is proposed to improve the intelligence and efficiency of the AGV system. The vehicles in the network can organize the network autonomously and share the information, including position, speed, direction, load status, etc., which can take full advantage of the distributed processing ability of the mobile vehicle and alleviate the load of the center server. Roehrig *et al.* [153] proposed an inexpensive solution for localization and tracking of small AGVs. In this solution, RFID transponders are used to realize global localization. Nugraha *et al.* [154] designed a line-follower AGV robot. The robot is equipped with an LED/LDR-based color sensor and an RFID-based identification/authorization system. It realizes choosing the route by detecting different color lines.

2) Carrying Based on ZigBee and Wi-Fi: In addition to RFID, ZigBee and Wi-Fi are two dominant technologies in this domain. Fig. 12 shows the wireless communications of AGVs based on the ZigBee network and Wi-Fi network.

Paper [155] presents an anti-collision method for an AGV. They use three ways to obtain the position of AGVs, by which the priority of AGVs that enter the areas of the collision is determined and the route of AGVs on a ZigBee network is controlled. In [153], an AGV localization method based on ZigBee is proposed. In the proposed method, AGV wheel encoder data and range measurements are obtained from a ZigBee network. Then, the location of the AGV is obtained through information fusion. Wu [156] presented an approach for navigation and guidance of a duo cycle autonomous robot vehicle by using ZigBee wireless control. By comparing the measured angular and location of the vehicle with reference points of a certain trajectory, AGV can follow a given path autonomously. Wang *et al.* [157] developed a distributed control system for AGV. The system uses Wi-Fi and CAN bus to realize real-time communication and further realized controlling the AGV.

3) Carrying Based on Other Wireless Communication Technologies: In addition, some new wireless communication technologies are gradually being applied to AGV.

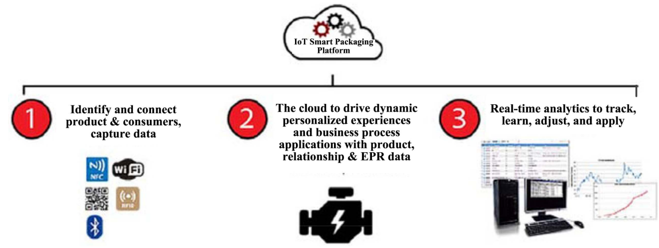


Fig. 13. Principle of work of smart packaging [160], [161].

Paper [158] presents a remote discrete model reference adaptive control for a two-wheeled mobile robot. In this model, all actuators, sensors, and controllers are interconnected by wireless communication. Here, the robot is controlled by the computer-based proposed controller through LoRaWAN wireless communication. Sun *et al.* [159] proposed a low-cost and high-precision positioning method based on cellular automata. In this method, AGV is equipped with wireless communication, which can complete the positioning through the continuous iteration of simple cell evolution rules in the cell space mapped by the positioning space.

In summary, AGV is a highly integrated carrying system. In the process of carrying, it needs to complete the goods reading, path identification, positioning, scheduling management, etc. This makes the use of a single communication method can not meet all the functional requirements. Therefore, it is necessary to integrate a variety of communication methods, including RFID, WiFi, ZigBee, LPWAN, etc., in the IoT system of AGV.

E. Smart Packaging

The packaging is the technology of enclosing or protecting products for distribution, storage, sale, and use. With the development of IoT technologies, the packaging market is changing from conventional packaging to interactive, aware, and intelligent packaging. In other words, smart packaging can leverage IoT and big data to establish a dynamic interaction with sensors on the packaging, such as RFID, NFC, Bluetooth, and smart labels [160]. Fig. 13 shows the principle of the work of smart packaging.

As shown in Fig. 13, smart packaging can improve tracking and tracing of packages by connecting to a network, which helps companies to make decisions on-the-fly. At the same time, its application helps product traceability to further reduce the risk of product recalls.

The research on wireless communication-enabled smart packaging mainly focuses on the design of smart packaging products and the application of smart package.

1) Packaging Product Design: In terms of packaging product design, it is mainly the design of automated packaging systems, which uses wireless communication technology-enabled IoT to achieve packaging automation.

Li *et al.* [162] proposed an IoT-based automated e-fulfillment packaging system. In this system, the robot, sensor, and smart machine are connected in a cyber network to achieve high velocity and flexibility of procedures and real-time information exchange, by which the robots accomplish the packaging task successfully and cooperatively. In [163], a prototype of a hybrid flexible smart temperature tag is proposed, which is designed with sensing, processing capabilities, and NFC compatibility. It can be used for potential temperature-sensitive product management and smart packaging to realize monitoring the environmental temperature.

2) Package Application: There are many applications of intelligent package products.

Biji *et al.* [164] introduced an intelligent food packaging system that monitors the condition of packaged food to give information regarding the quality of the packaged food during transportation and storage.

Chandra and Lee [165] proposed a cold chain logistics monitoring system that is based on IoT technologies. The system applies NFC, ZigBee, mobile communication network, etc. By identifying the unique NFC tag on each package, the system can monitor the product location. The iHome Health-IoT is proposed and implemented in [166]. On this platform, an intelligent pharmaceutical packaging (iMedPack) with communication capability enabled by passive RFID is designed, which can offer a promising solution for the medication noncompliance problem by automatically reminding the user and dispensing a certain amount of medicine on time according to the online prescription. Paper [167] presents a management platform to realize real-time tracking and tracing for prepackaged food supply chains. It proposes an integrated solution of using both the QR code and RFID tag. By this platform, a benign and safe food consumption environment can be ensured.

Kang *et al.* [168] proposed a wireless-enabled (13.56 MHz) smart packaging concept model that integrates the rectenna (wireless power supply), humidity sensor, and simple electrochromic signage on a poly(ethylene terephthalate) (PET) film using R2R processes. This model has the ability to sense the status of contents in the packaging actively and communicate the information wirelessly so as to enable more effective logistics and quality control. Paper [169] presents a smart food detector and safety monitoring system. Through the sensor and wireless communication module equipped on the package of the food, the status of food can be monitored. Based on the freshness of the food, an alert message will be sent to our mobile phone.

In short, in smart packaging, whether it is packaging product design or package application, the application scenarios of the IoT system are mainly short-range. The basic function of it is to realize the product readable and recognizable. Therefore, low-power short-range communication, such as RFID or NFC, is the first choice for such applications. With the gradual improvement of the intelligence of product packaging, more and more applications can real-time monitoring of product status by the package. For this application requirement, it needs to integrate sensor monitoring, embedded processing, and remote communication (such as mobile communication module) in packaging products. It will also be a big development trend for smart packaging.

F. Smart Distribution Processing

Distribution processing refers to all of the processing that is performed at the warehouse or logistics center before the products are shipped. The goal is to increase the added value of the product. There are many kinds of activities corresponding to distribution processing, such as packaging, sorting (grouping products into sets), labeling (applying labels), division (split as required), metering, and so on. For IoT technologies, more are applied in sorting and labeling.

1) Sorting: Sorting is the operation of sorting and stacking items in order of variety and order, it is a preparatory work to improve delivery and support delivery. In recent years, more research has been done on intelligent sorting.

Nawawi *et al.* [170] presented a reverse logistics sorting system based on RFID. In this system, the value of the product is recorded in the RFID tags mounted on the product, which includes all information on the materials and parts for recycling purpose activities. When the product entered the reverse logistics chain, reverse logistics operators will retrieve all information in the RFID tags to help to recycle products.

Shangguan and Jamieson [171] proposed a mobile RFID tag sorting robot. This robot is an autonomous wheeled robot reader that conducts a roving survey of libraries, manufacturing lines, and offices so as to achieve an exact spatial order of RFID-tagged objects in very close (1-6cm) spacings. Zhi and Poobalan [172] presented the design of an intelligent recognition and sorting system. In this system, a multilayer feed-forward ANN is used to recognize the product and duplex Bluetooth communication is used to communicate between the intelligent system and control computer. Paper [173] delivers an outline of an embedded wireless control system for the robot arm of sorting systems. It describes the architecture of the wireless sorting control system and wireless embedded-based control method.

Asghar *et al.* [174] presented a wireless pick-by-light system based on LoRaWAN for fast localization of items at the picking process in warehousing logistics. The proposed system offers long-range and minimum maintenance costs by using power-optimized LoRaWAN end devices.

2) Labeling: Logistics label is a value-added service for logistics in the supply chain process. The label contains the necessary information about the product, which is very important for product tracking and traceability. Therefore, labeling is an important link. The research on labeling is mainly focused on the application of smart labels.

Sun *et al.* [175] designed an anti-counterfeit system for identifying the origin of agricultural products based on GPS and encrypted Chinese-sensible code. The system uses RFID and Chinese-sensible Code based on an AES algorithm. It can collect and process the weight and location of the agricultural products, then print the anti-counterfeit label. Xu *et al.* [176] proposed a solution for RFID label printer to access the Internet through NB-IoT technology. In the proposed solution, NB-IoT technology is applied to RFID label printer to implement printer access to the Internet, which helps printer manufacturers to achieve remote fault analyzing and helps customers to solve problems of the printer. Paper [177] validates an RFID smart tag for real-time traceability and cold chain monitoring for food applications. This smart tag integrates environment sensors (light, temperature, and humidity sensors), a microcontroller, a memory chip, low-power electronics, and an antenna for RFID communications, which can be attached to the tracked food product to realize product tracking.

As mentioned above, in distribution processing, the process of sorting and labeling is closely related to the recognition of goods. Therefore, RFID is very common in such applications. With the development of long-range communication technologies and the continuous improvement of the intellectualized request, many research combine RFID with long-range communication technology to realize remote control of sorting and labeling, which is conducive to the optimization of the logistics process.

G. Smart Distribution

In recent years, modern logistics distribution continues to develop in the direction of informatization, digitization, networking, integration, intelligence, and flexibility. The applications of IoT technologies in intelligent logistics distribution are mainly reflected in the intelligent management of distribution centers and the development of intelligent delivery approaches.

1) Intelligent Distribution Centers: Intelligent distribution centers realize intelligent management by integrating technical equipments, such as intelligent handling, automatic sorting equipments, information processing systems, and so on.

In [178], an IoT-based route planning system (IRPS) is proposed. The system integrates IoT, Taguchi experimental design, and genetic algorithms to formulate the total product monitoring and optimal delivery route planning for multi-temperature food distribution. Gao and Tang [179] research the model of intelligent distribution to build the intelligent distribution center. The distribution center uses IoT technologies to realize identifying cargos, storing and collecting information, intelligent warehouse management, and automatic vehicle dispatching. Paper [180] conducts a case study on a CVS distribution center in Taiwan. It simulates the distribution center operations and costs after RFID technology is used. In [181], a smart distribution system based on dynamic WSN is described. In the proposed system, wireless sensor nodes called SmartPoints are used to monitor the environmental conditions and generate alarms when specific events are detected, which can monitor the quality of perishable goods, such as fruits, pharmaceuticals, etc.

2) Intelligent Delivery Approaches: Regarding logistics delivery, couriers delivery cannot guarantee highly time-precise delivery and cannot monitor the status of the goods in real-time. In order to combat the existing problems, a series of new delivery approaches for logistics delivery have emerged, such as intelligent containers, autonomous vehicles, unmanned aerial vehicles (UAV), etc. [182].

In [183], an intelligent container is proposed. In the system, WSN and wireless communication technologies are supporting technologies to supply the necessary information to autonomous processes. The system can monitor the inside parameters like the number and kind of loaded goods, the temperature, other environmental conditions, and the outside information (e.g., the changes in transport orders, costs, and the effects of the traffic situation). By this system, the improved and comprehensive supervision of goods is realized. Fig. 14 shows the communication infrastructure of the intelligent container. Dittmer *et al.* [184] presents an intelligent container that is a part of IoT to monitor the temperature and humidity for the delivery foods. Based on monitoring and providing information about the shelf-life of its cargo, the intelligent container will increase the transparency of the food supply chain.

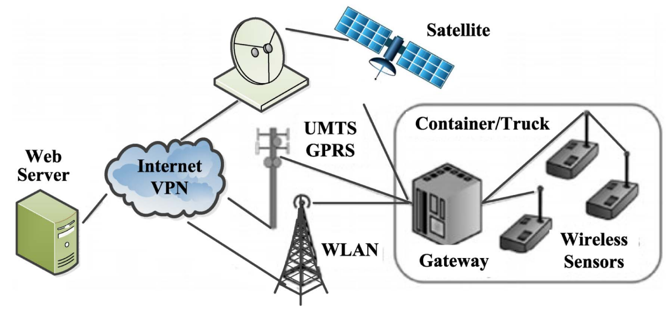


Fig. 14. Communication infrastructure of the intelligent container [183].

Sun and Zhao [185] presented a terminal delivery container, that is, a multifunctional parcel delivery locker system. It can realize SMS sending, password generation, and password authentication, by which the customs can be validated to get their parcels.

In recent years, AVs have been great potential in logistics delivery. Yu and Lam [186] proposed a novel autonomous vehicles logistic system (AVLS) to accommodate logistic demands for smart cities. In this system, vehicular *ad hoc* networks (VANETs) were set up based on dedicated short-range communications (DSRC, 802.11p) to accommodate the wireless communication demand. It can optimize the routes for the governed autonomous vehicles in consideration of various requirements imposed by logistic requests.

Song and Han [187] proposed an enhanced parcel delivery system based on IoT technology, which provides LoRaWAN as a dedicated global network for IoT and has the ability to figure out the current delivery route. Wang *et al.* [188] proposed a uniform parcel delivery system based on IoT. This system adopts IoT, computer network technologies, wireless communication, and cloud computing. Through this system, the package delivery process, including classification of packages, vehicle scheduling, path planning, transportation monitoring could be intellectualized.

UAVs are promising in relieving congestion in urban areas and improving accessibility in rural areas, moving the delivery off the road and into the air. Paper [189] introduces a comprehensive survey on UAVs and related issues. In this article, UAV-based architecture for the delivery of UAV-based and value-added IoT services from the sky are introduced, and the relevant key challenges and requirements are presented.

As stated above, smart distribution is an integrated application of IoT technologies. It involves multisensor acquisition, dynamic positioning, navigation positioning, multisource information fusion, decision-making optimization, and other aspects. Therefore, in this kind of IoT system, the used communication technologies are also diversified. The wireless communication technologies mentioned above, including the short-distance communication technologies, long-distance communication technologies, and mobile communication technologies are used according to different application requirements. Furthermore, due to the characteristics of multisource information, the requirements for information fusion processing will be higher in smart distribution.

H. Smart Information Processing

Logistics information refers to all information related to logistics activities (transportation, warehouse, and so on). In smart logistics, logistics information processing is essential. In fact, logistics information processing exists in every logistics scenarios. In addition to the application scenarios described above, logistics information processing based on IoT technologies is also applied to the design of logistics management models and logistics information systems.

1) Logistics Management Model: The logistics management model is the design plan for the expected production logistics system. Reasonable logistics management model can improve logistics efficiency and reduce logistics costs greatly. Therefore, the research on the logistics management model has always been an important content of smart logistics. Moreover, the development of wireless communications and IoT technologies has provided the necessary technical support for the optimization of logistics management models.

Paper [190] introduces an innovative logistics model and containers solution for efficient last-mile delivery. In this solution, data networks (Wi-Fi, UMTS, wired networks, etc.) connect the control units so that it can transmit to the information system of the logistics operator real-time information. In [35], a dynamic production logistics synchronization model is presented, which integrates cloud manufacturing and IoT infrastructures to enable a smart production logistics synchronization control mechanism with multilevel dynamic adaptability. This model can deal with the dynamics occurring in production logistics processes. Verdouw *et al.* [191] presented a reference architecture for IoT-based logistic information systems in agriculture food supply chains. The model combines IoT and cloud computing, which supports affordable solutions by utilizing technology enablers of the European Future Internet Program. Paper [192] presents an IoT-enabled dynamic optimization for sustainable reverse logistics. In this framework, an IoT-enabled real-time information sensing model is designed to sense and capture the real-time data of logistics resources, at the same time, a bottom-up logistics strategy is adopted to achieve the real-time information-driven dynamic optimization distribution for logistics tasks. In [193], a new logistics management model based on IoT and software-as-a-service is proposed. This model can help to improve the integration between physical resources and cloud services. Based on the proposed model, enterprises can develop their own cloud-based logistics management information systems.

2) Logistics Information Processing System: The logistics information system is an interactive system that provides information for logistics managers to perform planning, implementation, and control functions. According to different application goals, there are different logistics information systems, such as delivery path optimization, procurement process optimization, intelligent payment, etc.

Paper [194] describes a telematics system based on an intelligent van, which applies various wireless communication technologies, such as Bluetooth, RFID, Wi-Fi, etc. This system is capable of tracing pharmaceutical drugs over delivery routes from a warehouse to pharmacies without altering carriers' daily conventional tasks.

In [195], an analytical model is presented to compare RFID-based traceability information systems. The model uses the estimated costs of data capture and query processing to choose a solution for a given supply chain problem. Hsu *et al.* [196] developed an IoT-enabled one-stop logistics service provider process framework, which helps to solve the problems that the current material procurement process required excessive operation times and has poor data integration capabilities. Paper [197] presents a smart parking payment system based on NB-IoT and third-party payment platforms. In this system, the basic information management, charge management, task management, and business intelligence modules are implemented on the cloud server, which can improve the utilization of existing parking facilities. Burow *et al.* [198] showed IoT-based applications with hundreds of connected devices using the up-coming telecommunication standard 5G, which support a highly flexible production-logistics system and can satisfy the actual customer needs for custom-tailored solutions, services, and products.

As far as the current research and application are concerned, the biggest challenge of smart logistics information processing is the storage and processing ability of massive data, especially the fusion processing ability of multisource data information. This problem is also the current focus of researchers. Although the development of big data, cloud computing, AI, and other technologies provides solutions for this problem, the existing solutions are still not particularly mature. Therefore, the research on this problem will still be the key to the development of smart logistics in the next few years.

I. Summary

Nowadays, IoT technologies have been applied in all scenarios of the logistics industry to promote the development of smart logistics. At the same time, we can know that RFID technology is the most widely used in the logistics industry, especially in indoor application scenarios (e.g., warehousing, packaging, etc.), which is followed by ZigBee, Wi-Fi, and Bluetooth. In addition to the above technologies, cellular mobile communications (e.g., 3G, 4G-LTE, 5G, etc.), LPWAN (e.g., LoRaWAN, Sigfox) and satellite communication (e.g., VSAT) are gradually being applied in smart logistics, including indoor and outdoor (e.g., transportation, distribution, etc.)

VI. Challenges and Future Directions

The IoT technologies can help to realize the vision of future smart logistics, but also face multiple challenges. For example, due to the explosion of data generated by IoT devices during the supply chain process, data security, privacy, and resource management will be big challenges for smart logistics. In this section, we discuss these challenges from a technical perspective and present some future research directions.

A. Challenges

This part discusses three technical challenges: 1) data security; 2) data privacy; and 3) resource management.

1) Data Security: In the process of applying IoT technologies to achieve intelligent logistics, the information needs to be crossed multiple administrative boundaries and can be used for multiple purposes at any time, even for unknown purposes. As a growing number and variety of connected devices are introduced into IoT networks, the potential security threat escalates [16].

According to the study by [199], 70% of the most commonly used IoT devices contain vulnerabilities. The most common and easily addressable security issues include privacy concerns, insufficient authorization, lack of transport encryption, and insecure Web interface. Paper [200] discuss the detail reasons for the security issues of the IoT-based system. Specifically, the IoT system is highly dynamic, without well-defined perimeters, and highly heterogeneous with respect to the communication medium and protocols, platforms, and devices. In addition, human interaction is not scalable in IoT devices and this makes it difficult for security analysts or end-users to carry out security activities. Addressing such security challenges requires revisiting or substantially extending the current security solutions. Apart from this, paper [201] analyzes IoT security issues from a communication perspective. They analyze how the existing protocols and mechanisms to ensure fundamental security requirements and protect communications on IoT, and propose the open challenges and strategies for future research work in the area.

Although some solutions have been proposed, for example, grouping embedded devices into virtual networks and only presenting the desired devices in each virtual network [22], more effort is needed for it to be mature.

2) Data Privacy: In the logistics process, it contains a lot of personal information, product information, and enterprise information, which is communicated and exchanged over the Internet. Therefore, preserving data privacy is a sensitive subject and becomes an important research direction for researchers.

Paper [202] depicts the challenges to IoT deployment on preserving privacy from data collection policy and data anonymization. The authors propose that privacy can be ensured by restricting the type and amount of the collected information, the data anonymization can be ensured by cryptographic protection and concealment of data relations. Leaute and Faltings [203] presented a coordinating logistics operations model, which integrates with cryptographic techniques to allow several logistics service providers to coordinate without revealing agents' private information. A logistics information privacy protection method based on encrypted QR code (LIPPS) is proposed in [204]. It encrypts personal information and stores the ciphertext in the QR code with the segment encryption method. The logistics business operations can be completed by decrypting the corresponding information. Gao *et al.* [205] proposed a logistics information privacy protection scheme with position and attribute-based access control for mobile devices, which can provide privacy protection of both personal information and logistics information.

Although a lot of research on preserving privacy has already been proposed, many topics still need further investigation, such as data privacy in sharing and management.

3) Resource Management: As a result of the proliferation of IoT technologies in smart logistics, it requires the management of a large variety of protocols, data formats, and physical sensing resources in the operation process. This raises the question of how the resources provided by the devices can be efficiently managed and provisioned [206], that is, resource management is another challenge in smart logistics and it has also become a hot topic for researchers.

Some researchers have promoted resource management efficiency from the perspective of universal management methods. For example, paper [207] present a resource management model, in which Fog is used to manage resources, perform data filtration, preprocessing, and security measures. This model covers the issues of resource prediction, customer type-based resource estimation and reservation, advanced reservation, and pricing for new and existing IoT customers. Semasinghe *et al.* [208] explored some nonconventional game-theoretic models that fit the inherent characteristics of future large-scale IoT systems. This model can solve potential IoT-related resource management problems. Some have proposed the corresponding management strategies for specific resources. For example, Malik *et al.* [209] proposed game-theoretic mechanisms for resource management in NB-IoT-based IoT systems. They make the rate maximization problem considering the overhead of control channels, time offset, and repetition factor to build an interference aware resource allocation for NB-IoT. In [210], a dynamic resource management mechanism for the IoT-based cyber–physical production system is proposed. This mechanism realizes the load balancing based on Jena reasoning and Contract-Net Protocol technology, which provides a solution for complex resource allocation problems in current manufacturing scenarios.

B. Future Directions

Since smart logistics based on IoT technologies has attracted widespread attention and has been studied widely, its development can be influenced by a lot of other technologies. In addition to the aforementioned technologies, including AI, cloud computing, and big data, there are blockchains, cyber–physical system (CPS), 3-D printing, etc. For example, Tijan *et al.* [211] research the possibility of blockchain technology in sustainable logistics and supply chain management. Paper [212] provides a comprehensive survey on the literature involving blockchain technology applied to smart logistics. In [213], a CSP-based architecture is illustrated, which is for dynamic and modular control of single material handling equipment within a logistics system. Mohr and Khan [214] discussed 3-D printing and its disruptive impacts on supply chains of the future.

On the whole, with the continuous development of IoT, wireless communication technology, AI, and other advanced technologies, more and more researchers and enterprises have increased their research efforts on smart logistics based on multitechnology integration, which will also greatly promote the development speed of smart logistics.

VII. Conclusion

This paper provided a survey of the current IoT technologies applied to smart logistics. We began our discussion with some related papers and background knowledge of smart logistics. Then, we focused on enabling technologies for IoT in smart logistics. Furthermore, how IoT technologies are applied in the realm of smart logistics was discussed in detail, from the perspectives of transportation, warehousing, loading/unloading, carrying, distribution processing, distribution, and information processing. We also discussed some significant research challenges and future research directions in IoT-based smart logistics. In summary, research on applying IoT technologies in smart logistics is quite broad and a number of research issues and challenges lay ahead. Nevertheless, it is in favor of the community to swiftly address these challenges in smart logistics. This article attempts to briefly explore how IoT technologies work and when they should be used to solve problems in smart logistics. We hope that our discussion can help promote the development of smart logistics innovation.

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