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REVIEW ARTICLE

The Internet of Things for Logistics: Perspectives, Application Review, and Challenges

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ABSTRACT
The Internet of Things (IoT) vision enables multiple of resource-constrained embedded devices, objects, and humans to connect together through the Internet protocol for a ubiquitous data exchange. Logistics is considered to be a key player poised from this vision to achieve the full visibility and transparency through leveraging the pervasive interconnectivity to collect reliable and safe real-time data. In addition, the valuable information extracted and transformed from the IoT data can be exploited to create intelligent services and applications to improve the logistics activities as well as the overall performance of logistics operations. This paper aims at reviewing the state-of-the-art applications of IoT in the logistics sector. Although the adoption of IoT potentially gains huge benefits, there still exist barriers preventing the full adoption of IoT in the logistics. This paper also discusses such challenges that promise to expose a wide range of open research regarding the integration of IoT in the logistics domain.

KEYWORDS
Internet of Things (IoT); IoT technologies; IoT building-blocks; smart logistics; green logistics; physical Internet; logistics operations; efficiency and sustainability

1. INTRODUCTION

1.1 General Context

In reality, logistics is increasingly identified as a core industry sector promoting the strong development of the economy as well as other relevant sectors such as transportation, education. Due to various points of view and considered scopes, there exists a variety of definitions regarding the logistics. For example, the authors in [1] defined logistics as "the process of planning, implementing and controlling the efficient, effective flow and storage of goods, services and related information from their point of origin to point of consumption for the purpose of conforming to customer requirements". Meanwhile, Islam *et al.* pointed out that "logistics involves an integrated approach with the integration of information, transportation, inventory, warehousing, material handling, and packaging, and recently added security" [2]. They also sketched out five central components in the logistics managements including transportation, warehousing, inventory control, packaging, and information processing. From a broad view, many researchers such as authors in [3] considered the logistics as a combination of three flows, namely, physical flow, information flow, and financial flow. In this view, the ultimate role of logistics management is to ensure a full synchronization of three flows throughout the involved logistics activities, actors, and stakeholders. Regardless of multiple perspectives, the above concepts emphasize on the importance of information to achieve the ultimate goal of logistics services: *right products are delivered to right customers at the right time at the right place and in the right condition* [4]. The information will become more significant in the management of modern logistics since the logistics processes became significantly more complex and dynamic due to ever-increasing global competition, shorter product life-cycles, mass customization, and stricter quality requirements of customers.

Practically, information and communication technologies (ICT) have been widely deployed in the logistics-related sectors due to their capabilities in improving the information sharing and processing [5]. In particular, the development of advanced ICT enables the players of logistics chain to exchange the logistics-relevant information in real time. Furthermore, such exchanged data can be fully exploited to achieve the informed decision-makings, thus improving the performance efficiency of logistics processes. For example, the real-time decision-makings enable the logistics service providers to quickly respond to any changes of customer demands that, in turn, reduce the operational costs as well as improve the customer experiences [6]. From a business point of view, the logistics-relevant businesses can gain multiple benefits including increased sales, reduced inventory through the data analysis to predict the customer demands and market status [7]. Therefore, the application of ICT in the logistics management systems is becoming a key factor for strengthening the competitiveness of logistics businesses [8].

Recently, the Internet of Things (IoT) has been emerged as an innovative means, which revolutionizes the connection and communication of things [9,10]. Basically, things in the IoT paradigm include physical, and virtual entities, networks, systems that can be interconnected through integrated ICT such as Radio Frequency Identification (RFID), Wireless Sensor Networks (WSN), and Global Positioning System (GPS) [11,12]. In addition, such integration enables the things to be transformed into smart objects, which can communicate and make informed decisions ubiquitously and universally. In this vision, the logistics systems can take advantages of such pervasive communication to achieve the end-to-end visibility and traceability, which consequently increases the operational efficiency of logistics activities [13]. Accordingly, while the RFID and GPS systems enable the logistics assets and shipments to be tracked and traced in real-time manner the WSNs guarantee the quality of logistics shipments under any harsh environmental conditions due to the real-time sensing capability along the shipping trajectories [14]. Furthermore, the real-time and valuable data related to the logistics process enabled by the IoT-supported systems can be harnessed to improve the operational efficiency in terms of fleet and traffic management, inventory control, asset utilization, safety, and security. An intensive study conducted by both the IoT technology experts (CISCO[1]) and a logistics service provider (DHL[2]) implies that the employment of IoT can significantly improve the capabilities of logistics systems in terms of monitoring, controlling, managing, and optimizing the logistics activities [15].

All the aforementioned perspectives promise potential benefits, which can be gained from the application of IoT concept in the logistics through seamless interconnectivity among the related logistics processes and stakeholders of the chains. For example, real-time data sharing capability of IoT enables achieving the visibility and transparency of logistics operations. In addition, the decision-makings probably are improved to efficiently respond to the dynamic nature and uncertainty of the logistics-relevant environment. Moreover, the exchanged IoT can be fully exploited to offer intelligent services and applications, which in turn enhance the overall efficiency and sustainability of logistics operations. However, a few of the existing literature explores intensively the deployment of IoT in the logistics sector in both theoretical analysis and practical applications [16]. In this context, this paper aims at conducting an intensive survey on the current applications of IoT in the logistics-related domains, and then elaborating the opportunities and associated challenges exposed from the potential applications.

1.2 Contributions

The main contributions of the paper are summarized as follows:

- This paper reviews the state-of-the-art development of logistics paradigms, which aim at achieving the efficient and sustainable objectives through advanced technology-based solutions.
- Based on the huge potential of IoT, we present a perspective toward designing an IoT ecosystem for the logistics systems.
- An intensive survey is conducted and presented with respect to the existing IoT-based applications in the logistics.
- Although the IoT technology exposes the potential benefits for the logistics-relevant sectors, the adoption in the practices is challenging due to existing barriers. In this context, key challenges to adopt IoT in the logistics systems are identified in this paper. Indeed, further open researches and development studies are also discussed to overcome the challenges.

1.3 Organization

The rest of the paper is organized as follows: Section 2 presents an overview regarding the state-of-the-art developments of existing logistics, and IoT concept. Toward designing an IoT ecosystem for the logistics, Section 3 describes key enabling IoT technologies and associated building blocks. Section 4 presents the state-of-the-art IoT-based applications, which have been deployed in the existing logistics systems. Section 5 introduces the challenges of IoT deployment in the logistics. Finally, Section 6 concludes the paper and enumerates further developments. For the sake of clarity, this paper is organized as shown in Figure 1. In addition, the most used abbreviations and notations in this work are listed in Table 1.

2. BACKGROUND

This section overviews briefly the information of related context including the state-of-the-art development of logistics and IoT revolution.

2.1 Logistics and the Sate-of-the-art Development

The power of advanced ICT, particularly, the IoT technology promisingly enables an innovative transformation of

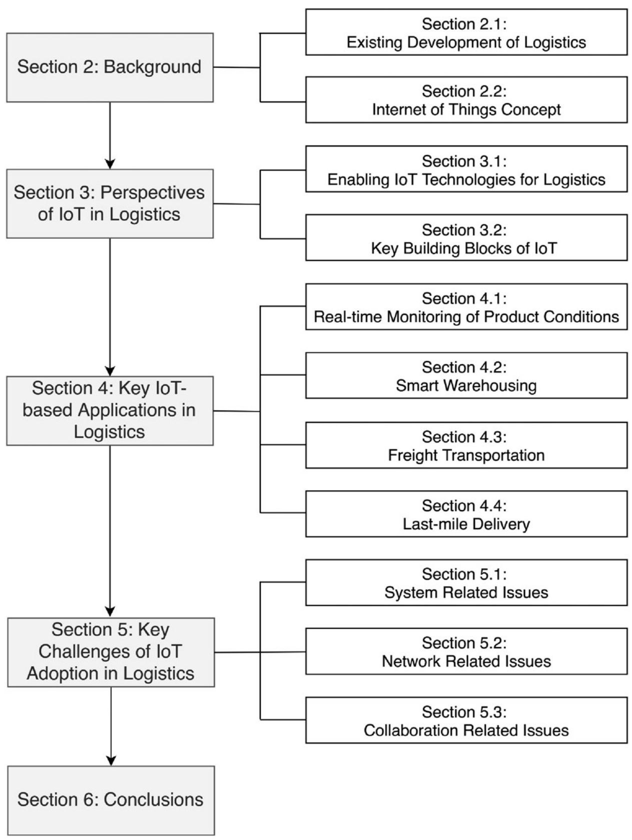

Figure 1: The structure of paper

Table 1: Table of abbreviations and notations

Abbreviations	Description
IoT	Internet of Things
ICT	Information and Communication Technology
PI, π	Physical Internet
RFID	Radio Frequency Identification
WSN	Wireless Sensor Network
GPS	Global Positioning System
RTLS	Real-time locating system
GPRS	General Packet Radio Service
NFC	Near-Field Communication
BLE	Bluetooth Low Energy
LPWAN	Low-Power Wide Area Network
NB-IoT	Narrow Band-IoT
LTE-M	Long-Term Evolution for Machines
D2D	Device-to-Device
M2M	Machine-to-Machine
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
V2I	Vehicle-to-Infrastructure
LAN/WLAN	Local Area Network/ Wireless LAN
MANET	Mobile Ad-hoc Network
VANET	Vehicular Ad-hoc Network

current logistics toward a sustainable and efficient global logistics. As a result, many logistics paradigms such as smart logistics, green logistics, Physical Internet that have been proposed and developed to achieve the vision. This section describes the state-of-the-art developments of these paradigms, which then can be summarized in Table 2.

2.1.1 Smart Logistics

The smart or intelligent logistics [17,18] is an approach which basically augments the intelligence characteristics of the system by embedding the advanced ICT to every component of logistics system such as freight-transportation [19,20], intelligent cargo [21–23], intelligent containers [24], and intelligent trucks [25]. Moreover, the type and level of the intelligence vary among application and methods, which can range from basic functionality such as product tracking and environmental sensing to problem detection and automatic decision-making and execution. By this way, the overall efficiency of this logistics paradigm is improved significantly through optimized decision-makings for the logistics operations such as the product flow management and automatic process control.

Another view as introduced in [26] indicated that smart products and smart services are two central components of a smart logistics. Accordingly, the smart products are capable of offering additional functionality such as identification, sensing, and algorithm execution enabled by accompanying technologies. Meanwhile, the smart services provide a set of valuable utilities and applications used to improve the efficiency of logistics activities. For example, control services aim at delegating of control tasks such as tracing and tracking, theft detection, and protection. Moreover, leasing services, risk services, information services, and complex services are additional types of smart services developed and integrated to fulfill logistics-related process requirements. In this view, the smart logistics are built up by several characteristics: identification, sensing, locating, and billing enabled by accompanying technologies such as identification (*e.g.* RFID, NFC, and bar-code), sensors, GPS. Extending this perspective further, every logistics-related entity can be transformed into smart objects thanks to the ICT integration. For instance, the smart containers used RFID, sensors, sophisticated data-processing techniques to realize several smart services such as real-time condition monitoring, real-time localization [27].

2.1.2 Green Logistics

Green logistics [28–31] is another efficient model that mainly aims at measuring and minimizing the impact of logistics activities on the ecological perspectives, especially environmental aspect [32] such as greenhouse gas (GHG) emissions, noise in cities [33]. Some of the proposed solutions in the literature are based on the optimization approaches of operation research models [34,35] to seek the optimal flows of products, information, and finance. In the methods, a variety of important factors such as transportation mode (*i.e.* plane, ship,

Table 2: Summarization of key logistics paradigms and proposition developments

Key logistics paradigms	Key propositions and developments	Objectives
Smart Logistics	• Integration of advanced ICT to the systems to enable smart/intelligent logistics assets: intelligent freight transportation [19,20], intelligent cargo [21–23], intelligent containers [24], intelligent trucks [25] • Developing and realizing smart services: tracking, sensing, controlling, autonomous decision-makings based on the information provided from smart assets [26,27]	• Improving the visibility, transparency of logistics activitiesc • Optimizing the efficiency of logistics processes through exploiting the digital data, which is captured by ICT throughout the logistics flows
Green Logistics	• Deploying the optimization approaches to optimize the flows of product, information, and finance [34–36] • Usage of emerging green technologies in the logistics-relevant sectors: green packaging [37], green transportation means [38–40] • Reusing and recycling the products and logistics assets [42–47]	• Reducing the impact of logistics activities on the environment (*i.e.* reducing GHG, noise, pollution, etc.) • Improving the efficiency and sustainability of logistics activities through optimized decision-makings
Physical Internet	• Innovating both logistics infrastructure and management strategies by morphing the model of Digital Internet [48–50]	• To achieve the maximized efficiency and sustainability in economy, environment, and society globally

truck, rail, barge, or pipelines), usage of intermodal transport (*i.e.* types of containers), usage of material handling equipment, types of fuel energy (*e.g.* gasoline, bio-fuels, electric, etc.) will be taken into account simultaneously so as to obtain the desired outcomes (*i.e.* minimal, maximal values) of objective functions for the logistics activities while subjecting them to a set of constraints. For example, electric equipment like fork-lift trucks should be used the most in the warehouses since they create indirect GHG emissions and they are flexible in short distance movements of inventories. In addition, reducing the travel time in warehouse by an optimal scheduling or routing is an effective and efficient solution to make the warehousing activities "greener" [36].

In another context, deployment of emerging green technologies is the main solution to green logistics perspective. For example, using green packaging with eco-friendly material contributes to a positive impact on the environment through elimination of the packaging waste, reduction of expenditure on waste disposal, and unnecessary transportation [37]. A case study conducted by Atkinson[3] reported that a replacement of corrugated cardboard with foam blocks brings about several significant benefits for Dell company including cost saving of shipping and damage elimination during loading and unloading shipments. Freight transportation is another important facet required to be make "greener" since it produces a major portion of environmental negative impact [38]. The green transportation mainly emphasizes on using innovated transportation means with low-energy consumption and lower emissions such as hybrid and natural gas vehicles and trucks [39,40]. The smart ICT-based systems such as single window systems, expert charging systems, and centralized and decentralized transport systems are recognized as enablers to achieve tangible benefits in terms of improving key logistics performance [41]. Reverse logistics is the complementary part of circular economy logic, which creates a closed-loop logistics to cope with the environmental concern by re-utilizing logistics resources/assets effectively and efficiently [42–46]. As defined in [47], the reverse logistics is

> the processes of planning, implementing, and controlling the efficient, cost effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal.

The reduction of environmental impacts by this logistics paradigm is enabled through sophisticated strategies for recycling and reusing products and logistics assets such as pallets, boxes, and transit packaging. For instance, the Waste and Resources Action Program[4] is organized and launched by the UK retailers, brand-owners, and suppliers to achieve a multiple objective of green environment through reducing the grocery and consumer packaging, household food and drink waste, and increasing the recycling process [3]. Accordingly, the program focused on conducting four specific projects to achieve the object. The first project is Argos[5], which includes designing reusable sofa bags and recycling them after using. B&Q is the second project that aims to eliminate product damage in transiting Carrierpacs for kitchen worktop.[6] Reusable transportation and storage system for large kitchen appliances[7] is the third project, which enables replacing the current disposable packaging used for large kitchen appliances with an alternative reusable transportation and storage system. Finally, the fourth project of the program is to obtain reusable transit packaging.[8] The project is carried out to reduce the impact of transit packaging on the environment and business economy. The proposed solutions are to reuse this disposal and then optimizing the usage of packaging.

2.1.3 Physical Internet – A Global Sustainable Logistics

Although the paradigms mentioned above partially can resolve the logistics-related issues, there is still a lack of a complete assessment regarding the global logistics situation and an associated end-to-end solution. In this context, a comprehensive investigation regarding issues of current logistics operations was conducted and reported in [48]. In this study, the authors claimed that the global logistics system faced with a grand challenge characterized by unsustainability and inefficiency in terms of economy, environment, and society aspect. In addition, they proposed and described Physical Internet (termed as PI or π) as an innovative logistics model to resolve the challenge effectively. Accordingly, to obtain the global sustainability and efficiency the PI requires a tremendous innovation encompassing application of advanced technologies for infrastructure, high-level cooperation and collaboration in both horizontal and vertical sectors, strategic planning and management to reshape the current logistics to be a global logistics system [49]. Originally, by taking advantage of features from the Digital Internet that moves data packets effectively and efficiently through a global Internet-connected network the key components constituting the PI include π-containers, π-nodes, and π-protocols [50] as illustrated in Figure 2.

Accordingly, the PI does not manipulate the physical goods directly but uses π-containers that encapsulate physical merchandise within them. In addition, like the data packets in the Digital Internet, these containers are standardized globally in terms of physical specification (*i.e.* smart, green, and modular) and functions [51]. In parallel, the π-nodes such as distribution centers or

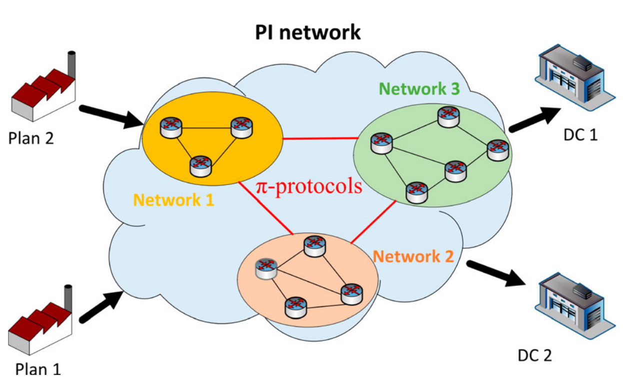

Figure 2: PI vision is viewed as an interconnected network, which connects all disjointed logistics networks by standardized π-protocols

warehouses play a role as smart interfaces, which ensure smooth input/output flows of materials and information. The π-nodes heavily rely on π-movers such as π-trucks, π-trailers to accomplish their tasks efficiently [52]. The last component of PI is π-protocols like the TCP/Internet Protocol (IP) in the Digital Internet, which are developed to control and manage the flows reliably based on the standardized rules and contracts.

The introduction of PI concept promises a potential innovation to reshape the structure of existing logistics systems toward a global interconnected logistics network in order to response to the grand challenge. Many proof-of-concept demonstrations by both experimental implementations [53,54] and simulation [51,55–57] are conducted to evaluate and examine the feasibility of this innovative concept. The main results of the evaluation process imply potential benefits of PI performance in the three sustainable perspectives, *i.e.* economy, environment, and society. Ultimately, ALICE (Alliance for Logistics Innovation through Collaboration in Europe) has promoted to develop the PI to be a reality of global logistic network by 2050, which enable interconnectivity and interoperability between involved logistics partners through the standardized infrastructure and protocols.

2.2 Internet of Things (IoT)

To date, there exist a number of perspectives with respect to the definition of IoT concept in the literature. IoT is considered as a single concept with multiple visions for extensive developments and various applications. Generally, the IoT paradigm can be viewed from three main visions: thing-oriented, Internet-oriented, and semantic-oriented as illustrated in Figure 3.

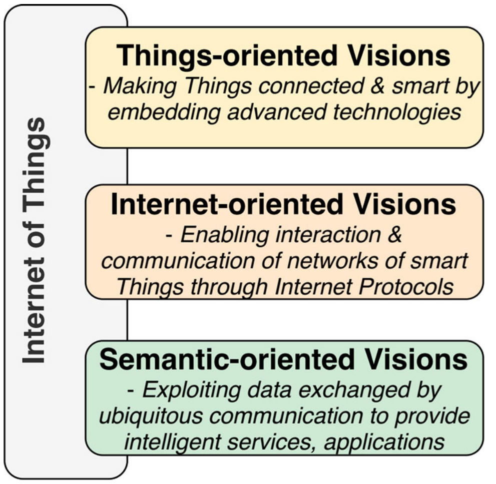

Figure 3: A single IoT concept with three visions for developments and applications

In the things-oriented vision, transforming physical and virtual things into smart things (objects) is a central research and development progress. In such a way, IoT stands for a technology to enable the transformation. Accordingly, the smart objects are capable of sensing, computing, communicating together, making decisions, and performing actions due to embedded emerging technologies such as identification (RFID, barcode), sensors, computing technology, and communication [58]. Meanwhile, the Internet-oriented vision concentrates on developing IP-based networks, which enable things to connect and communicate together. In this context, all the things (objects) in the IoT network are identified by IP addresses. For example, IPSO (IP for Smart Objects) alliance has developed an IP stack as a light-weight protocols to connect a large number of IP-enabled smart objects [59]. Due to an increasing number of devices joining in the IoT-enabled systems, a vast volume of data is generated and shared among the devices. In addition, a variety of data in terms of types, contents, and size generated by the heterogeneous devices expose the interoperability issues in the IoT networks. In this case, the semantic-oriented vision is emerged as an effective solution to address the issues. Accordingly, accompanying semantic technologies enable the IoT system to identify and extract the sets of raw data into homogeneous and heterogeneous formats and contexts. In particular, such the pre-processed data is then represented and interpreted in manners so that it is meaningful to the human knowledge and machines for supporting the decision-making [60,61]. For example, the IoT intelligent services are the semantic applications, which are developed based on the three perspectives mentioned above [62].

The underlying principle of IoT systems shared by these perspectives is the interconnection and interoperation between things in the network to enable the ubiquitous data exchange. In addition, the IoT systems can leverage and exploit the exchanged IoT data to improve the decision-makings through the intelligent services such as profound data analysis and prediction. Therefore, from the architecture perspective, the IoT systems consist of many components with different functionalities, which collaborate together to realize the functions and applications of systems. Basically, the IoT systems include four main functioning blocks: data collection, networking for transporting the data in the network, data processing for creating the application and services, and interfaces for accessing the applications by the end-users [62]. Regarding the sophisticated architecture and design, the works [63,64] identifies and describes up to 13 groups of technologies to construct the IoT systems such as identification, sensing, networking, to name a few.

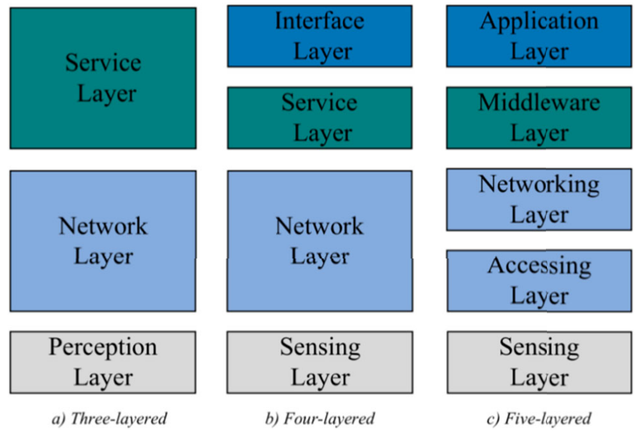

Figure 4: Three common architecture models and their layer mappings for IoT-based systems

Besides concerning the achievement of required applications, architecture is one of the significant factors impacting on the selection of appropriate enabling technologies for constructing the IoT system. As developed from the different perspectives, there has been no standard architecture to date practiced in IoT systems universally. For instance, an IoT-based system introduced in [65] simply consists of four parts: sensor nodes, gateways (GW), the public Internet, and the final applications. Most of the existing works propose to develop layer-based architectures for specific IoT applications. Basically, there are three common architecture models for the IoT-based systems, which are built from three, four, and five layers as shown in Figure 4.

For example, the works in [9,66,67] suggested that the IoT systems can be simply built-in based on three layers including perception, network, and service layer. Functionally, the first layer is to gather and/or pre-process the data generated by the connected things. Meanwhile, the second layer role is to transport the data to the upper layer or to other systems for further processing and usages. Finally, the service or application layer is to create the functions for the IoT system through applications and services for the users and organizations. For application in the industries, the architecture of industry IoT systems consists of three tiers: edge, platform, and enterprise tiers, which also have similar roles compared with the three layers: perception, network, and service, respectively [68].

By referring to the traditional OSI model, a more complex architecture of IoT systems as developed in [69,70] comprise of four functional layers, which are physical, transport, middleware, and applications layer. Such architecture is widely adopted in the practical systems to provide intelligent functionalities, services, and innovational applications. Recently, the International Telecommunication Union recommends to develop a sophisticated five-layer architecture for the IoT systems. These layers include sensing, accessing, networking, middleware, and application layer. In order to improve the connectivity reliability of systems, the accessing and networking layer are designed and developed thoroughly, especially in the industrial systems.

3. PERSPECTIVES OF IOT IN LOGISTICS

The deployment of an IoT ecosystem for a specific application involves selecting, building an appropriate infrastructure including physical entity (*i.e.* hardware), virtual entities (*i.e.* software, middleware, platforms), and the accompanying technologies. This section aims to highlight and investigate the key technologies as well as associated key building-blocks which can be applied for the logistics scenarios.

3.1 Key Enabling IoT Technologies

Since the performance of logistics operations is reliant mainly on outcomes of decision-makings, IoT will play an important role as data-driven technologies to improve the decision-makings through efficient data acquisition, processing, and analyzing. The IoT technologies have been summarized in a number of survey literature to date for a variety of IoT-based applications [62,71–76]. From the business perspective, data-driven IoT systems are widely applied and deployed in logistics-related enterprises [77] to fully make use of IoT data. Based on this vision, the key data-driven IoT technologies for the logistics applications can be grouped into three main functional blocks: data acquisition, connectivity, and data processing as summarized in Table 3 [78].

3.1.1 Data-Acquisition Technologies

3.1.1.1 Identification Technology. Identification technologies are indispensable in the IoT-enable systems since they are responsible for identifying automatically things (objects), just supporting effectively the device management. Such a functionality is essential in the logistics-related systems for facilitating the logistics activities such as inventory management, tracking. Practically, widely adopted identification systems include RFID, NFC, bar-code, or QR code systems, which are distinct from several technical factors such as communication technology, coverage of automatic identification, and types of identifier codes. Basically, the identification systems comprise two main parts: smart tags (*i.e.* RFID tags, bar-code labels, and NFC cards) and readers. The smart tags which are attached permanently to the physical objects store information relating to the object specification. Meanwhile, the readers can be standalone devices (*e.g.* RFID and bar-code readers) or integrated in the mobile devices like smartphone, personal digital assistant (PDA), handheld devices to capture and read data stored in the tags.

In addition to identifying, tracing, and tracking capabilities, the identification systems also serve as a communication channel and valuable data providers in the IoT

Table 3: Taxonomies of key enabling IoT technologies for logistics applications

Enabling Technologies for Data-Driven IoT	Functional Block	Enabling Technologies	
		Classification	Examples of key technologies
	Data-Acquisition *Generate and acquire relevant IoT data*	Identification	RFID, 2D-QR, Bar-Code, NFC
		Sensing	Sensors (i.e., bio-sensors, humidity, temperature sensors)
		Tracking	GPS, GPRS (General Packet Radio Service)
	Connectivity *Transmit IoT data to IoT devices and Cloud*	Global coverage	Cellular (2G, 3G, 4G, 5G), satellite
		Long range coverage	LPWA (Low Power Wide Area) (Sigfox, LoRa, NB-IoT, LTE-M)
		Short range coverage	Wi-Fi, Zigbee, Bluetooth, BLE (Bluetooth Low Energy)
	Data Processing *Filter, classify, sort, analyze IoT data to get insights into it*	Cloud Computing: The whole big IoT data is processed at the remote and powerful Cloud	
		Edge/Fog Computing: Sets of IoT data are processed at edge IoT devices or Fog nodes near to the data sources (IoT gateways, routers) to improve performances (e.g., reduced latency, balanced traffic load)	
		Big Data Analytics, Machine Learning, Artificial Intelligence: Relevant algorithms are used to analyze the IoT data and then predict the trends to improve decision makings	
		Middleware: Regardless the IoT characteristics (i.e., heterogeneity, complex structure), middleware relies only the IoT data to create intelligence applications, and services.	

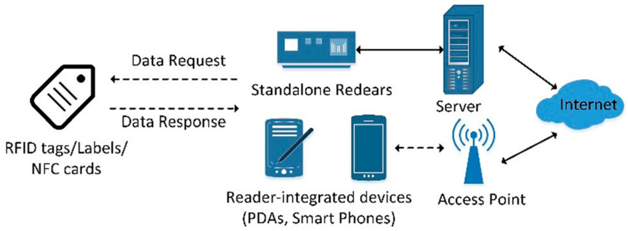

Figure 5: The typical architectures of identification systems in IoT-enabled systems

systems. Figure 5 shows the main components of identification systems and the associated architecture to connect to the Internet. Accordingly, for sharing the identification data, the identification systems can connect to the Internet via the Internet-connected servers or the access points.

Since the logistics-relevant operations involve multiple stakeholders, multiple parties, and even multiple nations the identification data becomes a key factor in improving the efficiency and productivity of operations. For instance, as exchanged correctly and timely, the IoT data can be exploited to enable real-time and adequate decision-makings on the handling, and management of logistics processes, especially in cases of changing conditions (*e.g*. customer demands, delivery routes). In addition, by equipping all the physical infrastructure of logistics systems (*i.e*. packaging boxes, material handling equipment, and vehicles) with the smart tags the identification systems can be further exploited to develop value-added services for efficiently monitoring, controlling, and managing the logistics processes. In such a way, the **SmartLocator** system as introduced in [79] is realized by combining the RFID system and the IR technology to track and localize the assets in warehouses in real-time. Similarly, a RFID-based localization system as proposed in [80] uses passive RFID tags to localize the pallets in the warehouse. The work [81] develops and presents a sophisticated system based on the RFID system to localize and provide three-dimensional position information of shipment packages in trucks or shipping containers. For practical tracking of logistics assets, an intelligent lot-tracking system named as **LotTrack** based on RFID and ultrasound technology is deployed in cleaning rooms of wafer factories where the chain of production processes are managed based on the dispatch list instead of an automated material handling system [82]. The **LotTrack** system developed by Swiss company Intellion to handle and keep tracking of positions of boxes across the production processes.

The rapid development of accompanying technologies enables the identification systems to be optimized and extend their functionalities [83]. In particular, since all the physical assets of IoT-enabled logistics chain are interconnected the unique identifier is required for each asset to efficiently support the global logistics activities. Recently, the EPC global standard provides a solution that allows identifying the logistics assets uniquely. Indeed, since the object identifier links to a set of relevant information including the physical status and context, this data also is shared and exchanged among the involved stakeholders of same logistics chain through an EPC Information Service (EPCIS[9]). The standard includes advanced security mechanisms, which ensure that only involved parties can access and use the captured information.

3.1.1.2 Sensing Technology. Fundamentally, the main role of sensing technologies is to perceive the status of physical objects and the surrounding environment conditions (*e.g*. pressure, temperature, humidity, etc.) through accompanying sensors, which are embedded in the objects. In addition, additional modules can be integrated into the sensors to extend their capabilities in the IoT context. For example, the sensors can communicate with each other through the embedded communication modules (*i.e*. transceivers) to exchange the sensing data. In most of IoT systems, all the data is pushed to base stations or servers (*i.e*. clouds), where the data is analyzed and used to generate the advanced services and applications for supporting the logistics-relevant operations such as monitoring, controlling. In addition, in order to reduce the overhead of data transmission to the remote cloud server the sensor can pre-process the raw data by the integrated computing components. Practically, a collection of multiple sensors can collaborate to form a WSN that is able to exploit much better the exchanged data to offer a wide range of valuable services and applications instead of a single sensor [3]. For example, a series of three systems using WSNs are proposed in the works [84–86] to monitor environment conditions inside twenty-foot equivalent unit containers, which usually contain perishable products. Fundamentally, the containers are equipped with a set of wireless sensors, which form an ad-hoc WSN inside the container to monitor the environment condition [87].

As shown in 6, the sensors are integrated permanently in the side walls of containers and the pallets for sensing the ambient conditions at every locations in the containers. In addition, through the radio signal strength indicator (RSSI), the base station of trucks can localize every sensors inside the containers for facilitating monitoring and controlling the conditions [84–86].

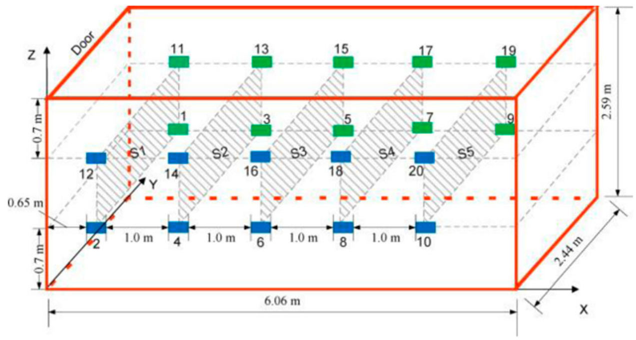

Figure 6: A WSN was deployed in the TEU container for environment condition monitoring [84–86]

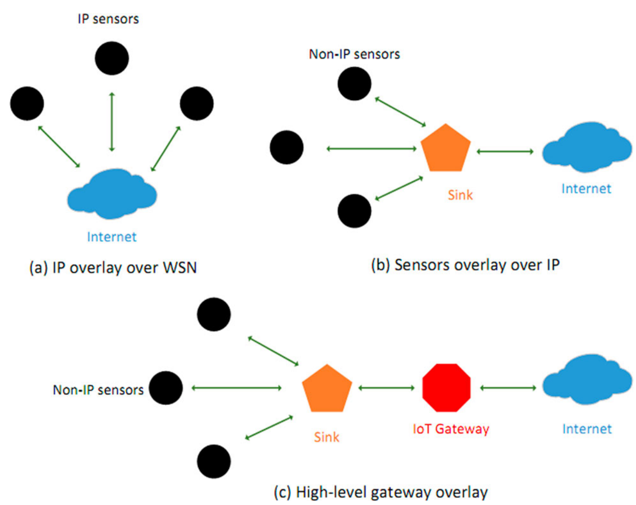

Figure 7: Connecting sensors or WSNs to IoT

To be an integral part of IoT systems, the WSNs can be connected to the Internet through three models: the IP overlay over WSNs, the sensor overlay over IP, and the higher-level GW overlays [88]. Figure 7 shows these three models used to connect sensors or WSNs to the Internet.

In the first connection model as illustrated in Figure 4(a), the sensors or WSNs can connect directly to the Internet since they are embedded by IP stack. In addition, addressing a massive number of sensors is feasible thanks to the integration of IPv6 (IP version 6) that offers an expansion of the IP address space for billions of smart objects [89]. Meanwhile, to connect a collection of non-IP sensors to the Internet, an intermediate node with dual communication interface is required. In the second connection architecture as Figure 4(b), a sink node collects all packets from the non-IP sensors and translated them into IP data packets before connecting to the Internet. Similarly, the third model in Figure 4(c) uses a high-level GW as a replacement of the sink node. In addition, the GW is empowered by advanced features such as computing, storage, and speed communication that improve significantly the quality of service (QoS) of IoT system.

Recently, the development of advanced technologies in microelectromechanical system can create microscopic-scale sensors [90–92] which can be embedded into every logistics assets including small-size shipments or packages. In addition, the intelligent sensor technologies can also offer a wide range of sensor types such as electromagnetic sensors, biosensors for extending the IoT-based applications, which improve the efficiency of logistics operations. In particular, the combination of identification data and sensing data enables the systems to achieve the complete visibility and integrity of whole logistics chains, thus obtaining the context-aware optimal decision-makings for the logistics management.

3.1.1.3 Tracking Technology. In reality, tracking is one of the vital services in the logistics management in order to achieve the visibility and transparency of logistics operations. Although the identification systems and the WSNs can be exploited to serve as tracking solutions, they can only be used to localize the logistics assets in limited spaces such as warehouses, distribution centers, and shipping containers. Meanwhile, to meet the additional demands such as fine-grained positioning, real-time information, global coverage, and reliability the specific positioning technologies including GPS, GPRS, and GIS are extremely required to track the logistics assets globally, especially valuable transportation means, feet, and important shipments.

3.1.2 Connectivity Technologies

The principle of IoT network is to connect all the things for data sharing pervasively, thus connectivity is considered as a complex and challenging aspect during designing the whole IoT systems. In addition to the variety and heterogeneity of networks with different protocols and standards, the connectivity of IoT-enabled logistics systems faces mobility nature of almost logistics assets such as packages, vehicles, material handling equipment. Furthermore, connectivity in the IoT network can be enabled by two types of technologies: device-to-device/machine-to-machine communication (*i.e.* D2D/M2M) and devices to the Internet through networking technologies such as cellular, satellite, WiFi, Bluetooth, RFID, NFC, and LPWAN. Therefore, setting up a connectivity landscape for the IoT-based logistics systems requires an intensive consideration of multiple aspects, which may impact on the performance of network connectivity.

For example, the majority of logistics activities are taken place in the indoor scenarios such as picking, loading, storing the items, products in the warehouses, distributions centers, and in the shipping containers. Technically, the short-range communication technologies can meet the connectivity requirement in the limited spaces. Therefore, the identification systems, WSNs, or LPWANs (*e.g*. Wi-Fi, Zigbee, Bluetooth, and BLE) have widely adopted to provide the communication channels between objects, and between objects, networks with the central management centers. However, selecting and deploying the most suitable connectivity solution take into account several conditions. For instance, since there are numerous objects in the warehouse, the connectivity technologies must mitigate the interference and reduce the impact of multi-path fading. Indeed, the presence of specific materials such as metal can block the radio signals, thus leading to the loss of communication.

Meanwhile, the logistics-relevant activities in the outdoor environment such as the freight transportation require the communication technologies to provide a wide, even global coverage. In this context, the traditional cellular technologies (*e.g*. 2G, 3G, 4G, NB-IoT, LTM-M, and 5G) can be applied since it ensures a continuous and reliable connectivity even these logistics assets are transported across urban or rural regions [93]. In addition, equipping the cellular communication technology with the valuable logistics assets (*e.g*. trucks, trailers, and ships) can reduce the operation cost in a long-term run because the cellular communication technology is the international standard and longevity technology [94,95]. Furthermore, with the assistance of V2 V or V2I communication, the transportation means can communicate together to optimize the operation efficiency. For instance, a truck can deliver a part of inventory to another nearby trucks directly instead of storing it in some warehouses or distribution centers to achieve a high inventory flexibility and optimize the performance efficiency. Especially, the latest development of cellar network technology generations (*e.g*. 4G, 5G) offers value-added services for multimedia transmission with the high, which, in turn, enable improving significantly the decision-makings.

3.1.3 Data Processing Technologies

Basically, a big data is used to define a complexity in multiple dimensions of data (*i.e*. velocity, volume, variety, etc.) generated by general IoT systems [96]. In the logistics systems, more levels of complexity are added in every dimension of big data due to high dynamic nature of a large number of logistics processes such as loading, unloading, sorting, and to name a few. Therefore, a set of sophisticated processing algorithms, analytics, and prediction is needed to handle such big data so that the valuable information can be maximally extracted for optimal decision-makings. Depending on the scale of IoT systems and operation requirements, the infrastructure for data handling is designed, deployed, and developed appropriately.

As the capabilities of local centralized systems fail to accomplish the data processing, the most of the existing logistics businesses are likely to use services provided by cloud computing technology (*i.e*. Platform-as-a-Service (PaaS), Software-as-a-Service (SaaS), Infrastructure-as-a-Service (IaaS)) [97–99]. Such a solution is cost-efficient for businesses since the services can be leased in the pay-as-you-go manner. In addition, rich resources of cloud computing paradigm (*i.e*. computation, network, and storage) bring with it additional benefits such as management simplification, flexibility, visibility, scalability, and sustainability [100–102]. The usage of cloud-based solutions releases workload of IoT devices, which are limited in resources (*i.e*. low and restricted computing capability, low power, etc.). Accordingly, the IoT devices serve only as data sources and communication channels that transmit the data to the remote cloud servers. At this site, the data sets are processed, analyzed, and transformed into valuable information, which is further sent to the subscribed applications for optimizing the decision-makings [96,103–108]. For example, a study as introduced in [109] shows that the application of big data analytics in the IoT systems enables the logistics enterprises to gain significant benefits in terms of improvement of driver safety, reduction of operating costs, and environmental impact reduction [109]. Practically, UPS logistics business used the big data analytics to derive the optimal delivery routes through analyzing the relevant IoT data (*e.g*. real-time GPS data, weather data, road maintenance data, and fleet and personnel schedules).[10] In addition, the analysis of the results suggested that the truck drivers can apply a "no-left-turn-policy" to improve the efficiency and sustainability of transportation performance.

Despite the powerful capabilities of cloud computing, centralized cloud-based computing solutions expose critical short-comings in several applications. Since the services require delay-sensitive responses or even real-time feedback, the use of cloud computing approaches may violate the requirements. For example, the response delay may not only be longer by large distance between IoT devices and remote clouds but also be exceeded as the network is unreliable. In particular, relying merely on the central data server to process a set of mobile IoT data generated by the mobile logistics assets might lead to an additional latency as well as unreliable outcomes.

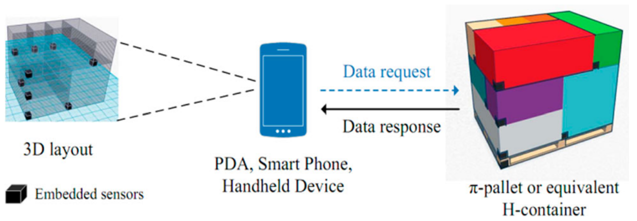

Figure 8: A handheld device (*e.g.* smart phone, PDA) can serve as a mobile fog node to provide valuable services

To address these issues, fog and edge computing technologies are developed and widely deployed in the IoT systems. Fundamentally, these techniques imply a distributed data processing approach instead of centralized cloud computing. Accordingly, the edge computing enables the edge devices such as sensors, mobile phones to process the raw IoT data locally. Meanwhile, the fog computing extends the functionalities and services of cloud servers to the closer locations of data sources [110–112]. The network devices such as IoT GWs, routers, or switches can extend their functions to act as the fog devices [113–115] to run the cloud-like services such as virtual machines. Additionally, these devices can process the IoT data to create the intelligent IoT services [116–121]. For instances, as illustrated in Figure 8, a smart phone can serve as a fog node to create and display the 3D layout developed from the works [3,112].

In reality, the complexity and heterogeneity of IoT data expose critical challenges in utilizing, managing it to offer valuable applications. The context raises the essential of middleware in the IoT systems since it is able to process the IoT data efficiently through the associated data fusion functionality. Accordingly, the middleware enables hiding the complexity of underlying infrastructure of IoT systems by abstracting and visualizing functions. In this way, the relevant information regarding processes, hardware specifications can be accessible by the applications through the interfaces (*i.e.* APIs). Practically, the variety of IoT system structure and specific application result in many methods to develop the associated middleware. The major methodology including event-based, agent-based, and service-oriented are widely accepted and developed in the practical embedded systems [122–125]. In particular, the service-oriented architecture is recognized as an efficient technology for developing the middleware for the IoT-enabled logistics systems, which can efficiently cope with the complexity and dynamic nature of logistics processes. In such approach, all the data collected from the physical layer can be appropriately extracted, classified, and then grouped to create the intelligent services via APIs. As a result, all the logistics activities can be monitored, controlled, and managed effectively through the services. In addition, with the support of three APIs: service discovery, service composition, and service access all the connected stakeholders across the entire logistics chain can be synchronized in a real-time fashion to use the services for optimizing the logistics activities [124–127].

3.2 Key Building Blocks

The capability of IoT technology enables smart concepts to be realized in the practical applications such as smart cities, smart grids, and smart factories. By modeling a smart data-driven system, we propose to develop smart IoT-based logistics systems, which can be constructed by three key building blocks, namely, smart objects, smart networks, and smart logistics information management system (LIMS) as proposed in our previous work [78].

3.2.1 Smart Objects

By embedding the accompanying technologies, the logistics assets can be transformed into smart objects, which can perceive the ambient environment as well as communicate with nearby smart objects to gather the IoT data [11,128]. Basically, the smart objects are composed of four main functional modules to fulfill these smart capabilities, which include data acquisition, connectivity, power, and processing module as illustrated in Figure 9.

Accordingly, the first and foremost important component of smart objects is the data acquisition module, which mainly acquires the relevant data including the ambient environment conditions (*i.e.* temperature, humidity) and the status of objects through the integrated data acquisition technologies (*i.e.* RFID, sensors, tracking). For instance, as the shipping packages or shipping containers are embedded with the sensors the sensing information including proprioceptive and exteroceptive content to make these devices active and especially self-configure if the status of shipments is changed [129]. In such a way, the smart objects can trigger (alarming) reports to the base station or nearby smart object regarding the unintended situations such as package open, theft. Meanwhile, the connectivity module enables the smart object

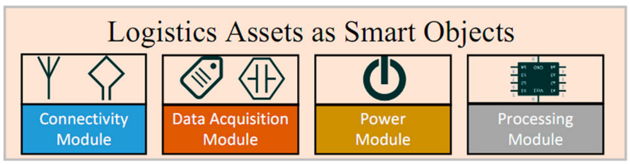

Figure 9: Four main modules integrated in a smart object for an IoT-based logistics system

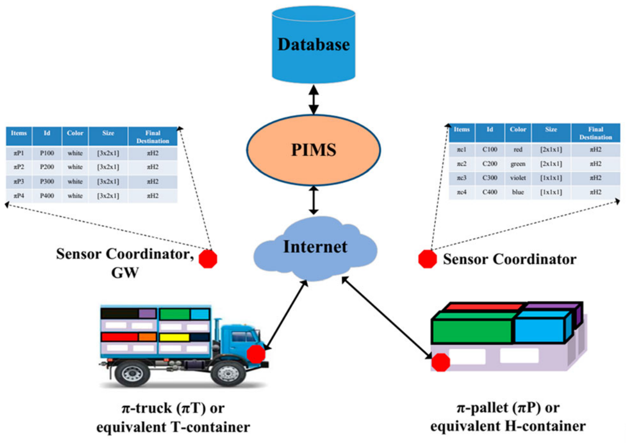

Figure 10: The example of smart πP and πT in the PI network, which can constantly monitor the both physical status and ambient conditions of π-containers through the integrated wireless sensors or gateways

to connect to other smart objects, networks, systems, and the Internet for sharing the acquired data. The processing module is the core brain of smart objects, which can run algorithms to accomplish several tasks to realize the smart functionalities of objects. For example, the vehicles can serve as fog nodes, which can exploit the acquired IoT data to provide local computation services and the informed decision-makings [130,131] even they are on the road to deliver the shipments. One typical service as developed in [132] is the 3D layout-based product monitoring applied in the PI paradigm. As illustrated in Figure 10, the wireless sensors or IoT GWs integrated in the π-pallets (πP) and π-trucks can provide 3D layouts specifying the allocations of π-containers. In addition, the status of π-containers is monitored in real-time since the equipped sensors constantly report to the GWs.

Finally, the power module provides the energy for all the integrated components of smart objects by either rechargeable or un-rechargeable batteries.

3.2.2 Smart Networks

Fundamentally, the IoT systems include a set of connected networks, which enable seamlessly interconnectivity and interoperability among the smart objects. In addition, the networks also serve as a means to deliver the IoT data from the sources to the data consumers, where the data is processed, analyzed, and got into insights. However, to deal efficiently with the specific characteristics of logistics systems and activities the networks of associated IoT-based logistics systems need to be transformed into smart networks. As shown in Figure 11, the smart networks in the context of IoT for the logistics

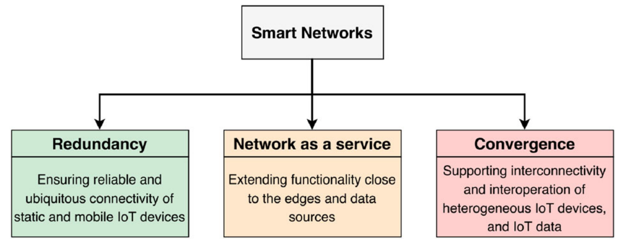

Figure 11: Three key properties of smart networks in IoT-enabled logistics systems

systems are featured by three factors: redundancy, network as a service, and convergence [78].

In practical, the presence of heterogeneous networks (*e.g.* RFID system, WSNs, LPWANs, MANNETs, and VANNETs) exposes critical challenges in ensuring the interconnectivity and seamless communication. In addition, the challenge is amplified by the mobility nature of the logistics assets, and flexibility of logistics processes, which probably cause the connectivity loss. Therefore, the redundancy mechanism is essentially included in the communication and networking aspect of smart networks to ensure reliable and ubiquitous connectivity for both static and mobile devices. In such the approaches, four major groups of wireless communication networks including wireless mesh, wireless LAN, cellular, and satellite must coexist to enable the seamless connectivity for the smart objects even in the cases that some of them can leave or join the networks dynamically. In addition, the deployment of network infrastructure for the IoT-enable logistics systems takes into account the public networks to support the connectivity for mobility of logistics assets. For example, the trucks or ships is able to exploit networking capabilities such as V2 V [133], IVC [134], V2I [135–138], and (V2X) [139] to communicate with the nearest trucks, ships or the nearest distribution centers for making the informed decisions during in motion.

In addition to the means to deliver the IoT data, the smart networks can exploit this data to provide the value-added services, which help in improving the overall efficiency of logistics activities. For example, as the shipment packages are equipped with wireless sensors, the network of these sensors can execute algorithms to provide valuable applications such as monitoring conditions at every positions inside the truck [112,140]. Recently, the emerging computing technologies (*i.e.* fog computing, edge computing) enables the network devices (*e.g.* routers, switches, GWs) to extend their functionalities by processing, analyzing the data closer to the data sources [141–143]. For example, the IoT GWs can process the data collected by WSNs and make decisions locally instead of sending them to the remote cloud, thus the QoS such as latency is improved significantly [144]. In particular, such computing techniques support efficiently the mobility of logistics-relevant activities through the mobile edge computing [145]. Furthermore, the big data analytics mechanisms and intelligent algorithms enabled by machine learning, artificial intelligence can be integrated into the network routers to extend and optimize their functionalities.

The last feature of smart network is convergence, which implies the capability of networks in processing all type of heterogeneous IoT data represented in four main forms: text, audio, image, video. Such ability enables the IoT-system to be interoperable, thus supporting providing ubiquitous service and applications. Recently, the next-generation networks develop an IP multimedia subsystem, which is a standardized platform for the delivery of multimedia services for the IoT systems [146–148]. The practical applications adopt such a platform to integrate the IMS in WSNs [149] or wireless actuator networks [150] for offering context-aware services.

3.2.3 *Smart Logistics Information Management System (LIMS)*

An LIMS is referred to as an interconnected network of high-computing systems including back-end systems, database servers, and/or remote clouds, and software such as warehouse management systems, transportation management system, and enterprise resource planning. As shown in Figure 12. In addition, LIMS uses the data

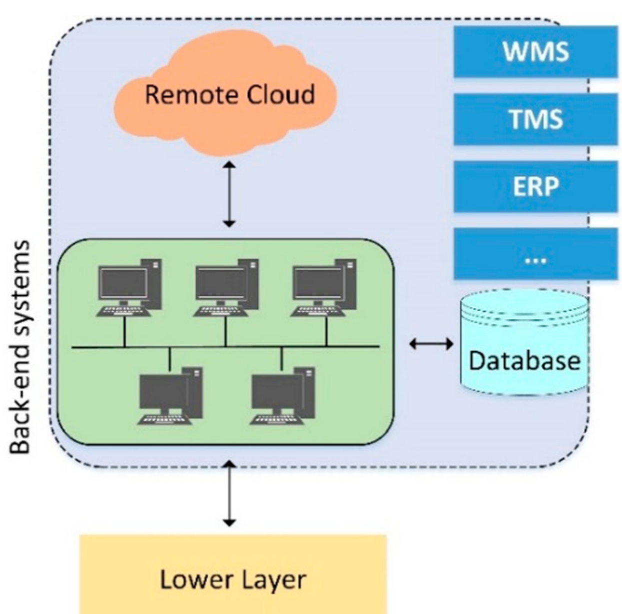

Figure 12: The architecture of smart LIMS

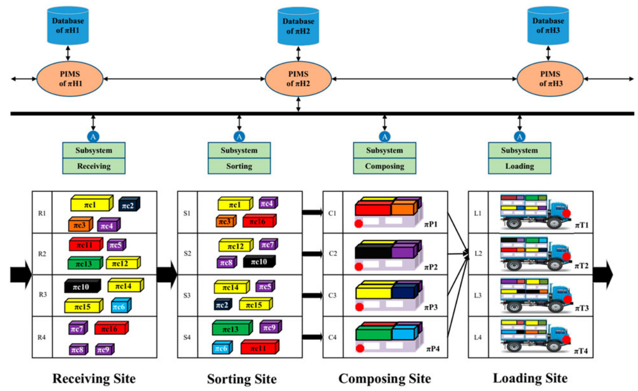

Figure 13: The structure of smart PIMS developed for π-hubs can efficiently control the π-container flows through ubiquitously interacting with smart π-containers, π-movers [78,132]

sent from the lower layer (*i.e.* physical layer) to provide the appropriate decision-makings on monitoring, controlling, and managing all logistics processes, logistics assets. In the context of IoT-enabled logistics systems, LIMS is transformed to be a smart system, which can fully exploit the IoT data to cope with the complexity nature of logistics-relevant operations and to maximize the efficiency of logistics activities.

For example, the smart LIMS should be distributed into intelligent sub-systems (*i.e.* intelligent agents), which enables monitoring and managing the logistics assets and associated activities efficiently.

In addition, the intelligence and activities of agents enable them to connect and share information to retrieve the best decision-makings. Such a system as displayed in Figure 13 was developed in the PI context for managing PI-HUBs, that can leverage the exchanged information optimize scheduling, processes (*e.g.* receiving, sorting, loading), and the utilization of assets [78,132].

4. KEY IOT-BASED APPLICATIONS IN LOGISTICS

Basically, the capabilities of IoT enable the systems to achieve the well-informed decision-makings based on the exchanged IoT data. In particular, the presence of uncertainty in the logistics activities is significantly mitigated by the advanced mechanism of data processing, analyzing in order to improve the overall efficiency of system. This section aims at highlighting the practical applications of IoT in the logistics activities, especially product condition monitoring, freight transportation, and warehousing activities. For readability, the descriptions of applications are then summarized in Table 4.

Table 4: Summarization of key applications of IoT in practical logistics domains

Application domain in logistics	Key developed IoT-based systems	Descriptions and objectives
Real-time monitoring of product conditions	• IoT-based systems for FCS s[151–153] • IoT-based systems for Cold Chain [154] • IoT-based systems for SCPF [156,157]	• Systems generally includes three major components: field devices equipped with WSNs, and RFID; communication networks (WLAN, cellular, satellite); and a backbone system with databases, computing servers • Objectives: real-time monitoring the food product along the supply chain • Findings: Ensure the food quality; Reduce food loss; Improve efficiency
	• IoT-based systems for Smart Containers: TRAXENS project, iCargo project [21–23,155]	• Systems embedded in the transportation containers include sensing and controlling, communication, and computing component • Objectives: Real-time monitoring and controlling the status of shipments inside the containers • Findings: Systems enable self-identifying the containers ubiquitously, context detection, autonomous decision-making
Smart Warehousing	• IoT-based systems for Inventory Management [161]	• Systems include RFID systems, IoT platform to receive data from RFID systems, and a webserver to display the historical inventory management • Objectives: real-time monitoring and management of inventory • Findings: Low cost deployment of systems; Efficiency in searching items
	• iLocate System [162]	• System uses active RFID systems and Zigbee wireless communication to localize the items in warehouse • Objective: real-time localization of inventory in the warehouse • Finding: achieving the fine-grained localization of items in real-time
	• PhyNetLab [163–165]	• Systems include physical layer with smart modular containers, edge layer for communication, and application layer for providing the warehouse management services • Objectives: Support material handling in the large-scale warehouse • Findings: reducing delay of logistics processes such as order picking, sorting
	• IoT-based systems for order fulfillment [166] • IoT-based systems for risk management [167]	• Systems comprise of RFID, WSNS, and MAS for collecting information and decision-makings • Objectives: warehouse management • Findings: Order fulfillment, improved warehouse visibility, transparency, and efficient risk management
Freight Transportation	• IoT-based systems for real-time freight tracking [168,169] • IoT-based systems for parking support [170] • IoT-based systems for freight management by Intel • Simple Link project	• Systems equip IoT-relevant technologies (RFID, WSN) to vehicles and mobile fog-based computing systems for distributed decision-making • Objective: support efficient freight transportation • Key findings: efficient management of shipments; enable real-time tracking function; support searching the parking pots through communicating with intelligent transportation systems; support routing in case of uncertainty of road traffic conditions
Last-mile Delivery	• Intelligent Lockers [172] • Smart Mailboxes [173]	• Systems build IoT-enabled last-mile distribution center near to customers. Managers and customers use a middle app for communication and decide place and time to receive the orders • Objective: efficient last-mile delivery • Findings: short time delivery delay and satisfy the customers' comfortability

4.1 Real-time Monitoring of Product Conditions

Monitoring the conditions of products and shipments is essential in the logistics activities, especially products that are sensitive to the ambient environment. Thanks to the IoT technology, the monitoring activity enables the systems and stakeholders to guarantee the quality of products along the logistics chain by identifying, sensing, and tracking functions.

Currently, the food supply chain has been widely poised to benefit from the potential of IoT to ensure the quality of food product as well as improve the efficiency and sustainability of chains. Fundamentally, the IoT-based solutions can be developed to track the status of food products and then make the informed decisions on management and control of the product quality [151]. In this way, applying the IoT technology probably addresses the complex issues of logistics chain management related to the geographical and temporal processes. The pervasive interconnectivity of IoT system enables the products to be tracked and monitored along an end-to-end trajectory. For example, a framework in [152] is proposed to develop an IoT system, which can monitor the entire FSC (*i.e.* in farm-to-plate manner) from precise agriculture, to food production, processing, storage, distribution, and finally consuming at the end consumers. According to the framework, the proposed IoT system uses WSN nodes and RFID tags/readers as field devices to collect the data related to the product states in all the consecutive processes. The data is transported to the remote central stations including databases, computing servers by the interconnected networks such as WLAN, cellular, and satellite networks. At the central stations, all the real-time IoT data is processed and analyzed using the advanced processing techniques such as three-tier information fusion, big data analytics, and cloud computing service to get insights into the data sets. The data handling outcomes then are used to predict the life-cycles of products, thus supporting the management systems to take the informed decisions on using, managing the products efficiently, and re-planning the entire supply chain. The work [151] also presented the results after implementing the framework in practical contexts, which promises a promising IoT-based solution to enhance the overall efficiency of FSC.

The intelligent cold chains are developed to minimize the impact of environment conditions on the food quality along the chain, especially the fresh food and vegetable products [153]. Accordingly, the intelligent systems using the sensing and communication technologies ensures the real-time monitoring of ambient environment and product states, thus enabling the well-informed controlling [154]. In this method, the fresh food products are carried by the intelligent containers such as InBin,[11] which are equipped with the IoT technologies (*e.g.* RFID and WSNs) to monitor the quality of food. In addition, the local GWs are deployed in the containers for receiving the data of food quality and environment conditions, which are then analyzed to make the appropriate decisions on maintaining the quality of products.

By exploiting the embedded technologies, additional features can be integrated into the smart containers to improve the efficiency. For example, the project **iCargo** aims at developing the intelligent cargo with multi-function including self-identification, context detection, status monitoring, and autonomous registering and decision-making [155]. In addition, an associated cargo tracking system is constructed to exploit these iCargo capabilities to provide the complete visibility of shipment to the customers [21–23]. In addition to the tracking optimization, the functions of iCargo also improve the usage of assets through monitoring the asset utilization to avoid the under-utilized or empty trucks. Furthermore, since the intelligent cargo can perceive the context such as traffic and weather conditions the accompanying routing mechanism can response effectively to the cases of disturbance or uncertainty.

Although the smart containers have been widely developed and adopted in the practical applications, none of them are globally standardized with respect to the information capture, consistent communication, and multimodel transportation. To support tracking and monitoring the shipment conditions in the global scale, the project TRAXENS[12] has been realized smart multimodal containers. In addition, the containers provide the universal data exchange, thus enabling the interoperability and integration within the different systems of different business.

In addition to using the smart containers, connecting constantly the trucks to the warehouses and distribution centers can reduce significantly the quality degradation of food products along the cross-regional transportation, especially the perishable food products [156]. The authors in [157] have been developed an IoT-enabled supply chain for perishable food, which enables capturing the real-time information of shipments. In addition, the information can be shared with the IoT-based Supply Hub in Industrial Parks [158,159] to support maintaining the quality of foods. For example, as the trucks are unable to deliver the products with the ensured quality to the end of route they can be stored temporarily to the nearest hubs.

4.2 Smart Warehousing

Practically, serving as distribution centers, routers, and storages warehouses imply a key enabler to the success of logistics activities. However, the complexity nature of warehouses characterized by the presence of various logistics assets (*e.g.* shipments, material handling equipment, end vehicles) and dynamic of logistics processes (*e.g.* loading, picking, composing, storage, routing, etc.) exposes critical inefficiencies in the warehousing management. The inefficiency is mainly caused by a lack of instant and adequate information related to the asset status, locations, which are required for appropriate decision-makings regarding inventory control and management and errors of manual handling systems. In this context, developing IoT-based systems is an efficient solution to manage the distribution centers since a full visibility benefited from the ubiquitous connection of inventories enables the logistics processes to be optimized [160]. Depending on the used technologies, developed algorithms, and target applications a variety of IoT-enable systems is developed and deployed accordingly.

Such a kind of systems as introduced in [161] uses the RFID technology to constantly update the dynamic data of inventory. In this way, specific inventories can be tracked and searched in a real time efficiently. Figure 14 illustrates the schema of such system. Basically, the products stored in stockrooms of warehouses are attached physically with RFID tags. Meanwhile, the RFID readers are placed appropriately in the gates of stockrooms to frequently read the tags once the products are moved in or out. In addition, **NodeMcu** broads serve as IoT platform to transport the data from the readers to the central server, which is enabled by **Raspberry Pi 3** platform for further processing.

This platform can communicate with the webserver via Internet or Wi-Fi connection. In addition, a web server was developed as an interface to display the data of products and facilitate the real-time searching of items in the warehouse. Due to low-cost implementation and user-friendly interface for product tracking the prototype of system potentially can be extended and used in real-world applications.

In a similar method, the authors in [162] have proposed a newly fashioned real-time locating system (RTLS), namely, **iLocate** that uses active RFID for asset management in indoor environments through automatically tracking, visualizing, and localizing the objects. In principle, **iLocate** exploited RSSI (received signal strength indicator) measurements of RFID signal to perform the localization algorithms such as fingerprinting. The fine-grained locations of targets are determined with the help of reference tags, which are installed appropriately on affixed facilities such as the shelves of each rack. In addition, **iLocate** employed the frequency-hopping

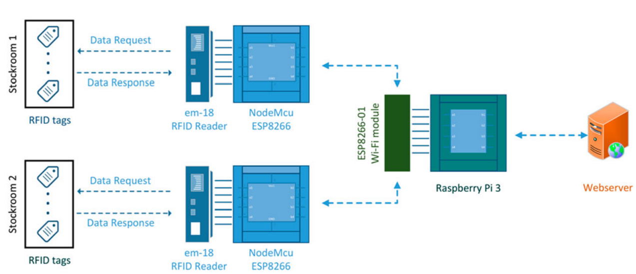

Figure 14: The architecture of IoT-based system for inventory management of warehouse as introduced in [161]

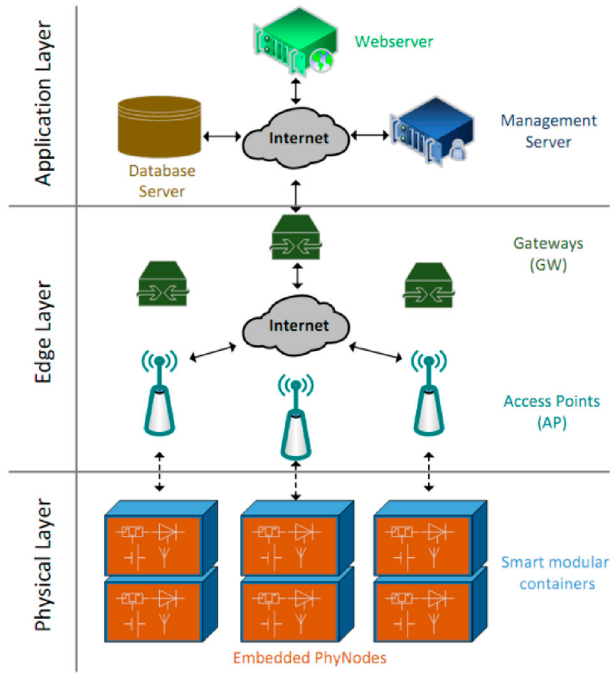

Figure 15: The architecture of IoT-based PhyNetLab testbed introduced in [180]

technique to derive efficient schedules of tag-tag communications, which in turn helps in eliminating the noise and multi-path impact. Consequently, that improves the accuracy of localization algorithm. To deploy the proposed approach in a large-scale RFID network and IoT applications like warehousing activities, **iLocate** used ZigBee-based networks that support transmission of data over long distances by multi-hop manners. The associated experimental results and the real project implementation have shown the performance superiority of the proposed system over several related RTLSs.

The work [163] introduced **PhyNetLab** as a real large-scale warehouse testbed developed for important applications in the warehouse management such as the inventory control, and material handling. Technically, the IoT-enabled system made of cyber-physical objects and smart sensing devices, namely, **PhyNetNodes** [164,165] includes three layers: physical layer, edge layer, and application layer as sketched out in Figure 15. The first layer encompasses smart and modular containers which are attached physically with corresponding **PhyNodes** at their fronts. The IoT customer-developed nodes, in turn are equipped with a set of professional modules such as a solar cell, a display, radio interface, numerous sensors and a rechargeable battery. Using radio chip CC1200, these nodes can communicate wirelessly with the network infrastructure including access points, GW in the second layer.

These edge devices are connected to the Internet by an optimized Long-Term Evolution link to deliver the IoT data from the IoT physical devices to the application layer for further storing, processing, analyzing by database servers, web-servers, and management servers. The primary results from the implementation of testbed show that this IoT-based system can help in reducing the delay of material handling processes such as order picking or sorting, thus to improve the efficiency of warehouse management.

Recently, collaborative warehouses such as classical cross-docks, urban distribution centers, logistics cities and city hubs are widely used in supply chains since they allow several suppliers, manufacturers and distributors share physical spaces and logistics information to enhance overall performance. However, such resource sharing strategy is challenging the smooth flow of products since they are shipped not only from various provider sources but also to a variety of client destinations. The challenge leads to an urge to develop efficient warehouse managements, which can exploit as best as possible the shared resources to improve the performance of relevant logistics activities. One of such methods has been developed and introduced in [166] or efficient-order fulfillments. The bottom-up approach is based on an IoT infrastructure which comprises of RFID, sensor-enabled ambient intelligence, and multi-agent system (MAS) to collect IoT information from products and resources at the bottom of the chain and then transmit it to the intelligent agents (*e.g*. smart sensors, desktops) for local decision-makings. Particularly, although the tasks can be completed locally the bottom-up method enables the global efficiency to be achieved due to improved warehouse visibility, traceability, and transparency.

One of the critical issues in the warehouse management refers to inherent risks of hazardous accidents which are caused by incompatibilities of proximity products. Mutual handling errors, unplanned movements of products within the warehouses are among typical sources that lead to misplacements of incompatible products. To avoid the risks, an efficient approach is introduced in [167] to obtain the optimal product allocation with respect to the compatible constraints of products. According to the proposed scheme, a virtual layout is developed to perfectly review the products and their locations in the warehouse. The IoT technologies such as RFID, WSN and an MAS are used to create the layout, which enables detecting any possible risks in the warehouse in a real-time manner. For example, as two nearby items can expose any risks such as explosion, the virtual layout triggers an alarm after analyzing algorithms are accomplished.

4.3 Freight Transportation

Freight transportation is referred to as a pivotal logistics activity to transport the shipments from the sources to the destinations (*i.e*. customers). Practically, the efficiency and service quality of this process are highly impacted by the kinds and status of transportation modes as well as the associated strategic planning. Although an optimal planning is set up for an end-to-end transportation route, it may not ensure an optimized outcome finally. For example, the traffic congestions, road conditions, and even the inclement weather conditions directly influence on the speed of delivery and the operational costs. Such typical issues are resulted in from a significant lack of real-time information regarding the conditions of field realities, and current states of transportation means along the routes, thus leading to the lack of well-informed decision-making on the re-planning processes.

In this context, applying IoT probably addresses the issues since it provides a means to collect and transport the valuable information to the local or remote base stations, which then run the sophisticated algorithms to derive instant and adequate decision-makings. Accordingly, all the logistics transportation means and vehicles are equipped with the acquisition technologies (*i.e*. identification, sensing, and tracking technologies) to perceive the data related to their status (*e.g*. positions, fuel energy, engine, etc.) as well as the ambient environmental conditions. In addition, the IoT-connected vehicles can communicate and exploit the intelligent transportation systems to realize the innovative services such as real-time monitoring [19,20,168] along the delivery routes [169]. Furthermore, enabled by the V2 V communication the connected vehicles can share the valuable information to improve the overall efficiency of logistics activities. For instance, available spaces in the parking areas can be informed to the driving vehicles for support parking. In particular, the trucks can share the load on the roads without the intervention of intermediate warehouse in order to improve their resource utilization and to reduce the delivery time [170]. Such all the perspectives are included in a smart freight management system, which is developed by Intel[13] to monitor and manage the high-cost, and high-risk shipments. Accordingly, the system integrates the smart sensors to the shipment packages to sense the status of shipments as well as the ambient environmental conditions. The data collected by the sensors is sent to the smart GW, which is embedded into the vehicles. In particular, the edge intelligence is integrated into the GW to enable the local data computing and analysis, which improve the system performance in terms of delay and operation cost. Furthermore, as the data sets require sophisticated algorithms for processing, computing, evaluating, and analyzing they are transmitted to the remote clouds.

In another vision, simple Links[14] is developed as a smart tracking system for the business, which provides an integral item-tracking solution through digital links. Fundamentally, the digital links are referred to as the information relationship between the shipping items and their containers. For the consumer good logistics, the containers include shipment packages, pallets, shipping containers, trucks, and warehouses. In addition, the information which is captured and collected by low-cost identification such as RFID, QR code is constantly updated to the business management systems. In this way, all the historical data regarding the relationship between the items and their containers is tracked and traced at any time of requests. In particular, the management system of business adopts the data analysis mechanism to detect the faults and predict the future item states. The system that is demonstrated in the practical applications shows the positive impact in terms of ecological and economic benefits.

4.4 Last-Mile Delivery

The last-mile delivery is referred to as the final stage of logistics chains, which puts the ordered shipments to the hands of customers. Although the customers can be individuals or business the services face the challenges in common such as high cost, inefficiency, security, and lower customer satisfaction [171]. In one hand, the last-mile delivery heavily depends on the objective factors including the transportation traffics, weather conditions, deliverer behaviors, and even the availability of customers. On the other hand, the optimized strategic planning on the delivery service cannot adapt to sudden changes such as place of shipment reception of customers due to the lack of real-time information. In addition, delivering the shipments to the doors of customers exposes the security-related issues, which may reduce the customer experience. In this context, the IoT-enable solutions promise improved services since they can respond efficiently to any changes of customer demands as well as the objective conditions along the routes. In particular, the IoT-bases services enables both the shippers and customers to track the shipments in real-time. One of these solutions is intelligent lockers or smart mailboxes, which are IoT-enabled smart storages [172,173]. These delivery locations are distributed in the regions of customers to enable a flexible schedule of delivery time and location. In this way, the shippers can adaptively optimize the routes to put the shipments on the most appropriate boxes so that the customer satisfaction is minimized. In practical, the logistics service providers and retailers developed IoT-based mobile apps such as United Parcel Service (UPS)[15] or MailHaven[16] that enable the customers to track purchases and receive exclusive deals from retailers.

5. KEY CHALLENGES OF IOT ADOPTION IN LOGISTICS

Despite huge potential benefits achieved by the application of IoT in the logistics industry, practical integration of these pairs (*i.e.* IoT and logistics) is still limited due to the inherent existence of significant challenges. This section highlights these specific issues in three main groups: system, business, and collaboration as shown in Figure 16 and discusses possible solutions as future directions for the paper extension.

5.1 Systematic Issues

5.1.1 System Efficiency and Sustainability

The first and foremost concern is the feasibility of IoT adoption in the logistics since inherent issues raise several questions on the overall performance of IoT-based system in the logistics operations.

Although the goal of logistics operations is to obtain the efficiency and sustainability, adoption of IoT in this domain might impose a paradox. For example, since the physical assets of logistics are equipped with smart devices (*e.g.* RFID, sensors) usually powered by batteries, saving their energy to prolong their operation lifetime is importantly prioritized. These IoT devices can be requested any time to provide relevant information that is needed to develop and offer the intelligent decision-makings and services. Thus they may be active always to fulfill such significant requirements. To reduce the

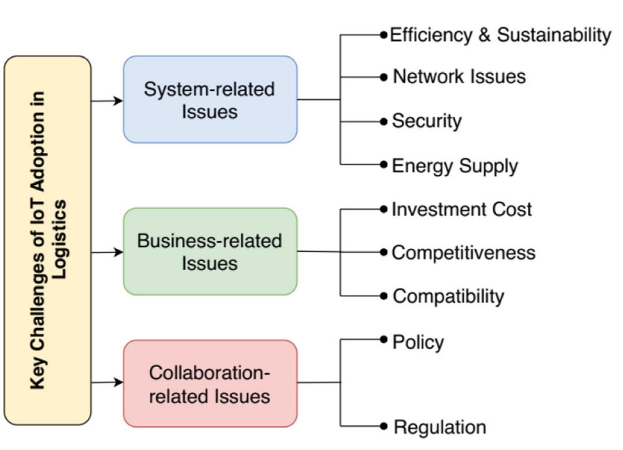

Figure 16: Key challenges of IoT adoption in logistics

power consumption the WSN node might be asleep (low-power mode) most of the time and it will only wake up to acquire the sensor data or to communicate to another node. Therefore, it requires an analysis framework to investigate and evaluate the sustainability of system when utilizing the IoT technologies.

5.1.2 Connectivity Network Issues

Connectivity enabled by communication and networking technologies is the core factor to realize an IoT system, which in turn, enables effective multi-model, global freight transportation. However, to design and deploy a reliable and pervasive connectivity network in the IoT-enabled logistics system faces crucial challenges.

Although the redundant communication mechanism applied in the smart network building block is recommended to achieve the ubiquitous interconnectivity within the IoT ecosystem the reliability of communication is adversely impacted by inherent causes. First of all, the nature of logistics environment can negatively influence the quality of wireless communications. For example, the presence of RF obstacles such as steel construction, thick wall of warehouse, and containers reduces significant the ratio of received packets since they degrade the power of RF signals. Besides selecting the appropriate radio with considerable receiver sensitivity, selecting the materials for the smart objects, especially the packaging boxes, containers must be paid close attention to mitigate the unreliable communication.

In addition, the presence of multiple networks operating under the same frequency bands probably degrades the quality of communication due to interference. For example, a majority of WSNs (*e.g*. Zigbee, Xbee) uses the ISM (industrial, scientific and medical) bands for enabling the wireless connectivity in the practical applications. Therefore, as the networks are located in proximity locations, the radio interference cause loss of communication links. Although, several solutions such as blocking mechanisms for the mobile phones, transmission power control techniques are proposed to reduce the impact of interference on the wireless communication the unreliability issue is still critical in the context of logistics applications because a high density of smart objects (*i.e*. logistics assets) is available in limited spaces like warehouses.

5.1.3 Security

Security is a critical aspect in not only general IoT systems but also logistics industry. Since the interconnection and interoperation are a prerequisite for IoT-based logistics processes, the digital security becomes extremely important at any level. Integration additional capabilities to the smart objects (*i.e*. data storage, identification, location monitoring, etc.) impose potential risks along the shipping trajectories. Especially, the digital transaction is more focused by hackers and cyber attackers. Recently, Blockchain technology has been emerged as a key solution to the security issues in the IoT environment [174]. Basically, all product relevant data collected through the identification and WSNs is recoded in the blockchain. In addition, each product is assigned by a unique digital ID, which secures all data access along the product lifecycle as well as processes of logistics chain. In particular, this technology is increasingly adopted in supply chain, logistics management not only to enhance the security regarding the digital data exchange [175,176] but also to improve the efficiency [177,178].

5.1.4 Energy Supply

As key building block of the system, the smart objects pose a real design challenge on several levels. One of these significant issues is related to the supply of energy to the smart objects that may be used for frequent activities, namely, capturing the environmental information, processing it, storing it, and exchanging it. According to the sizes and requirements of innovated designs, there are numerous solutions that will supply energy to the smart objects, but there is no obvious solution up to now. Batteries, physical connections, energy fields, and a combination of these technologies which are shared with the IoT pose considerable challenges. For example, using the batteries for supplying the energy for the smart objects probably cause potential risks (*e.g*. explosion, fire) for the hazardous materials, especially shipments. In another context as the smart objects are delivered by the airplane, the radio signals emitted by the smart objects can interfere with the communication system of air planes, thus exposing controversial issues.

5.2 Business-Related Issues

5.2.1 Investment Cost

Realization of an IoT ecosystem heavily relies on the integration of accompanying technologies such as RFID and IoT platforms. As a result, the raising of system cost might be the first challenge for the logistics operators and businesses. In addition, the firms must establish a suitable infrastructure that is adequate to them. Especially, to exploit the full potential of IoT a high-computing system with high cost of investment is required to manage, process, and analyze a big data, provided by a vast number of smart objects through a dynamic flow of logistics operations. Moreover, the deployment of new technologies and the associated ecosystem might lead to additional costs of business used for activities such as training, familiarity to get used to operating, controlling, and managing the technology operations. However, a better trade-off between the investment cost and efficiency and profitability of logistics management can be achieved potentially through extending more functionality, services based on the employed technologies. For example, in addition to the sensing function, the sensors can be collaborating in forms of ad-hoc networks to provide more functionality such as tracking, tracing.

5.2.2 Competitiveness

From business aspect, enterprises have no or lack of trust to exchange their own logistics-relevant data, especially sensible one through the shared IoT-enabled networks. Therefore, only a limited amount of data should be shared by certified partners that presents as a significant barrier to deploy the IoT-enabled solutions.

5.2.3 Compatibility

Another critical concern in considering the IoT adoption in the logistics-related business is the compatibility of IoT technology and its solutions with the existing infrastructure. Especially, the IoT technology can be denied to be integrated in some legacy systems, which have been ensuring the efficient operations for a long-term.

5.3 Collaboration Related Issues

Collaboration is used in this work as a wide term, which relates to the coordination and harmonization of control and management policies and regulations issued by not only business but also countries.

5.3.1 Policy

Existing literature assessed that these policies and regulations can be harmonized and coordinated by technology application and organization improvement for facilitating the logistics-related processes such as international freight transportation [179]. However, insufficient collaborations due to different and even isolated policies still serve as a significant barrier to adopt and/or accelerate the IoT adoption in the logistics domain.

5.3.2 Regulation

In particular, toward a global logistics network as vision of Physical Internet all involved partners, stakeholders, and actors are required to share information, protocols, and resources to obtain the maximized transparency, efficiency, and sustainability. As analyzed in the previous sections, IoT serves as a key role to enable the interconnectivity and data exchange between any parties of logistics chain universally and ubiquitously. However, due to the different regulations of countries, accomplishment of the agreed regulations for smooth operation of transnational shipment activities is difficult to be realized. For example, the shipments can be traveled through different countries by multi-modal transportation that might have different regulations related to customs, security, transport mode, and other significant issues.

6. CONCLUSIONS

The application of IoT concept has brought the transformation of logistics into innovated model, which potentially drives a greater operation efficiency and sustainability thanks to advanced abilities of IoT-enabled technologies. This paper, firstly reviews developments of current logistics that encompasses several paradigms such as smart logistics, green logistics, and physical Internet. Toward obtaining a global efficiency and sustainability, such logistics models are relevant heavily on ICT to optimize the logistics activities efficiency through efficient exploitations of shared information. Particularly, recent IoT technologies that are recognized as an ultimate means for information exchange solution herald new ways of greater efficiency gains. Thus, this promises a potential perspective with respect to the application of IoT in the logistics. This paper also describes the perspective through sketching out an IoT ecosystem that can be applied for the logistics fields. The system encompasses key enabling IoT technologies with data-driven orientation, and key building blocks including smart objects, smart networks, and smart logistics information management system. On the basis of IoT ecosystem, the state-of-the-art development of IoT-based solutions is presented to highlight their applications to the logistics activities such as product condition monitoring, warehousing, freight transportation, and last-mile delivery. However, the practical integration of IoT-logistics pair is still in an infancy stage since there are still many immature in systematic, network, and collaboration perspectives. These barriers are discussed intensively for further open researches regarding new development space IoT-based solutions for the logistics enterprises.

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