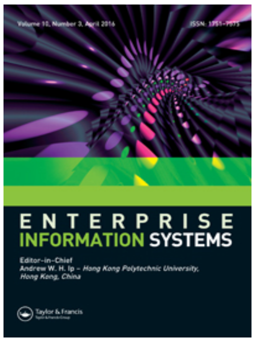

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Design theory, modelling and the application for the Internet of Things service

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ABSTRACT
The Internet of Things (IoT) makes it possible for us to sense the physical world and locate objects in it using the enabling technologies associated with IoT. Compared with traditional information systems, IoT enabling technologies can help acquire real-time data necessary for managing enterprise business process. An IoT system should have an ability beyond integrating enabling technologies and traditional information systems that are only used to access environmental data. This paper begins with a literature review of IoT-related issues and a discussion of the difference between traditional information service and IoT service. Three principles for IoT service design from the perceptive of service classification, coordination and compatibility are proposed. The paper also proposes a utility model for resource allocation in order to improve IoT service performance, and an application involving a cold chain visibility platform is given to illustrate our research.

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Internet of Things; service; utility; model; application

1. Introduction

Following the Internet, the development of the Internet of Things (IoT) has been ongoing in recent years. The concept was initially named and discussed by Kevin Ashton in 1999. It then became increasingly recognised through the research and discussion by the MIT Auto-ID Center (Angeles 2005). IoT blurs the line between the digital and the physical world and is considered to be the next-generation network or future Internet (Yan et al. 2008; Zorzi et al. 2010; Castillejo et al. 2013). Although a unified academic concept for IoT is still under discussion, a consensus has been reached by many researchers that IoT is a system that is pervasive around us, including a variety of functional objects such as RFID tags, sensors, actuators, mobile phones, etc. With the implementation of unique addressing schemes, it has been possible for a device to interact with its neighbouring devices to meet the desired goals (Yan et al. 2008; Atzori, Iera, and Morabito 2010; Giusto 2010).

Reviewing the development process of the Internet, IoT is much more than a technological achievement (Xu 2012). Valhouli (2010) stated that trying to determine the market size of the IoT is like trying to determine the market for plastics. It was difficult to imagine that plastics could be in everything in that period. Consequently, many new opportunities shall be foreseen for individuals as well as for business and other organisations, but also for the society as a whole (Xu 2012). However, challenges always come hand in hand with opportunities. The service issues resulting from IoT development lie in both new applications and in the upgradation of traditional information service, i.e., smart logistics and storage (Hribernik et al. 2010). This paper would investigate the service issues resulting from IoT.

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In the context of enterprise application, business requirements such as cost reduction and globalisation require the delivery of the right information to the right people at the right time for decision-making purposes (Valhouli 2010). IoT enabling technologies, such as Radio Frequency Identification (RFID), Electronic Product Code (EPC) and Wireless Sensor Networks (WSNs), are able to provide technical solutions to help realise this demand by sensing the environment, identifying products and locating objects. However, from the view of system, cooperation among IoT facilities is much more important than the telecommunication and simple integration. The purpose of IoT application is to optimise business and service modes, rather than briefly promoting efficiency by integrating IoT enabling technologies into traditional information system.

Although traditional information service, such as the Internet searching service, e-mail service and e-business information sharing systems, still plays an important role in today's life and business process, the information service has to face the new arrival of the IoT. Some researchers have started using the term 'IoT service' recently, but it still lacks systemic description. The main aim of this paper is to systematically describe and analyse information service issue related to IoT. We emphasise the term – IoT service – which refers to the information service based on IoT facilities. Specifically, this paper is organised as follows: Section 2 reviews the state-of-the-art on IoT, information service as well as IoT service, and some brief discussions are provided; Section 3 proposes and explains the IoT service design principles which give the reference architecture for IoT service design; in Section 4, a utility model for IoT service is generated, and the corresponding analysis is conducted; Section 5 provides the design process of IoT service in the context of a supply chain visibility platform as an illustration of the above-proposed theories and model; and Conclusion is provided in the last section.

2. Related work and problem statement

2.1. *Visions of IoT*

Based on the common idea of IoT mentioned above, different perspectives of IoT are proposed in the literature. As reviewed by Haller, Karnouskos, and Schroth (2009), these perspectives can be concluded into things-oriented view, Internet-oriented view and semantic-oriented view.

Things-oriented perceptive mainly focuses on how to code and identify objects and how to make actuators smart. Auto-ID lab (http://www.autoidlabs.org/) and EPC-global (http://www.gs1.org/epcglobal) hold this view. Research on RFID, Near Field Communication (NFC) and EPC technologies as well as their applications is the main study subject.

Internet-oriented vision emphasises the importance of network, and researches the technique or resolutions for connecting objects and sensors into a whole network via the Internet. Improved Internet Protocol (IP) is recognised as the most appropriate technology to realise this heterogeneous network. One of the typical research organisations who holds this view is IPSO (IP for Smart Objects) Alliance (http://www.ipso-alliance.org/). The work done by 6LoWPAN (IPv6 over Low power Wireless Personal Area Network) work group of Internet Engineering Task Force (IETF) is of significance to the researchers with the Internet-oriented version. They are trying to establish an improved IP system for WSN that enables seamless connection between WSN and the Internet.

In the semantic-oriented vision, context-aware, reasoning and data-mining technologies play important roles. Because more information from the surrounding objects are collected or sensed in IoT environment, the corresponding algorithms (Barnaghi et al. 2012; Lin, Sandkuhl, and Shoukun 2012; Barthel et al. 2013; Castillejo et al. 2013) are studied to resolve issues related to how to represent, store, interconnect, search and organise information generated by the IoT (Dinter 2013).

However, most of the current studies are not from the perspective of the whole system and only focus on specific points that can be seen as IoT enabling technologies. Enabling technologies are significant to a well-designed and developed IoT system, but more works are needed from the system view to guide the design, development and running process. The term 'IoT' is semantically composed by 'Internet' and 'things'. 'Internet' is the 'hosting network' that enables all kinds of objects and network access, and 'things' are the ends and terminals of this Internet-based heterogeneous network which are responsible for input and output. So the different views stated above are actually the different research directions or levels within the IoT. Indeed, objects must be coded, identified and connected into the Internet, and then these objects can be used to provide advanced service (such as semantic service) to users. Thus, to some extent, we consider IoT as a combination of the Internet and data-collecting networks (DCNs). The Internet helps long-distance data transmission and advanced data processing, while the DCNs realise things identification, environment sensing and short-distance data transmission.

2.2. *Network components of IoT*

Although communication is not the final purpose of IoT, network is an essential component for an IoT system. It provides users with a fast and cost-effective way to share information, bridges geographically dispersed users and provides service opportunities. Although various network technologies exist that are adaptable in IoT systems (Atzori, Iera, and Morabito 2010), we can still classify them into three types according to their basic functions: identifying networks, sensing and actuating networks as well as the intermediary networks.

The networks composed by identifying devices can identify and transmit the identities of things or objects, such as RFID and EPC network (Huang and Li 2010; Kortuem et al. 2010). Sensing and actuating networks are used to collect raw data, analyse the environment and conduct the corresponding actions according to the preset algorithms.

Intermediary networks play the role of connecting all kinds of identifying networks, sensing and actuating networks. The Internet has benefited from new technologies over time and with each new technology opportunity arises, e.g., Web 2.0 allows users to actively participate in information creation and cloud computing shifts the Internet to focus on service provisioning (Atzori, Iera, and Morabito 2010). As the most widely used network system, the Internet, consequently, becomes the most appropriate one to act as the intermediary network, which works well in supporting e-commerce, social networking and many network-based enterprise applications.

Some researchers consider sensing and data transmission as two different IoT architecture layers (Xu, He, and Li 2014). However, sensing and transmission cannot be separated in many cases. For instance, the sensor nodes are sensing devices as well as the network node. Daniele et al. (Huang and Li 2010) integrated computing, communication and identification as a whole research topic in the IoT study, while taking the network system aiming at long-distance data transmission as another topic. We propose that the network components in IoT should be classified by their functions rather than by the technology attributes. Thus, although WSN and the Internet are both network technologies, they play different functions in the IoT system. Internet is a typical Intermediary network. And we call the networks with the functions of identifying and sensing as DCN. Table 1 shows the data-related issues between DCN and the Internet. For DCN, data is collected from the physical world, and actuator or individual plays the role of sink node. Efficient transmission is the main purpose of data processing in DCN. The data that supports service is always processed deeply on the Internet, while the data in DCN are always used as raw data.

As shown in Figure 1, DCN and the Internet blur the cyber barrier between the human and physical world, which makes it possible for us to sense the physical world by cyber ways. With the

Table 1. Data in DCN and Internet.

	Data collecting network	Internet
Data source	Physical world	Individual/Information Systems/Other networks
Data sink/destination	Actuator/Other networks	Individual/Actuator
Data type	Raw	Processed

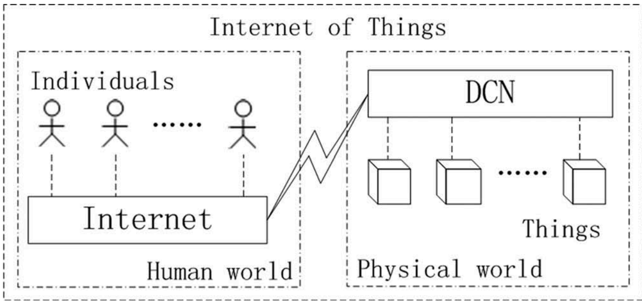

Figure 1. Paradigm of IoT.

context-aware technology, IoT is easy to realise personalised information service based on the real-time data and context information from DCN.

2.3. *Information service and IoT service*

2.3.1. *Information service*

IoT provides a new paradigm for information service. In this vein, it is necessary to outline the definition of information service before discussing IoT service.

Although it can be learned that the grammatical meaning of the term 'information service' is a service that provides (serves) data/knowledge/information somehow, it is meaningless without a context (http://infoserviceonto.wordpress.com/2010/06/23/what-is-an-information-service/). We searched the Web of Science database with keyword 'information service' and made simple statistics on the research fields of these papers. Table 2 shows the top five research directions, and it indicates the majority of researches with the keyword 'information service' focus on the Information and Communication Technology (ICT), library science and business economics, all of which cover more than 70% studies in this field. Obviously, current researches on information service mainly concentrate on the service based on information technology and library science. As for library science, most of the studies focus on how to efficiently provide readers the information they need (Borko 1968; Kettinger and Lee 1994; Rubin and de la Peña McCook 2000). Thus, library service can be regarded as an application branch of information service, i.e., library acts as an information provider, and ICT is the necessary facility in modern library service.

According to the survey above, it can be generally concluded that information service is a service provided by information facilities ranging from information organisations to information systems (Wang, Wang, Ding, et al. 2013, Wang, Wang, Zhang, et al. 2013). In this paper, we mainly discuss the service issues related to ICT. Accordingly, information service here refers to the service provided by an information system that provides user data, information or knowledge in an automatic way. Corresponding supporting techniques and design methodologies for information system will determine what kind of service can be provided and the possible providing ways.

Table 2. Research direction of information service.

Research direction	Number of records	Percentage
Computer science	32,608	33.933
Engineering	19,869	20.676
Telecommunications	11,295	11.754
Information science library science	8670	9.022
Business economics	8597	8.946

2.3.2. *IoT service*

Recently, the term 'IoT Service' has appeared in many literatures (Bohli, Sorge, and Westhoff 2009; Alam, Chowdhury, and Noll 2010; Lee and Crespi 2010; Xing, Wang, and Li 2010; Atzori, Iera, and Morabito 2011; Ma 2011; Seskar et al. 2011; De et al. 2012; Shang, Zhang, and Chen 2012; Wang et al. 2012; Xu 2012). Xu, He, and Li (2014) presented how the IoT affected the spatial ramification of service offerings and service business from the view of social science. They gave the definition of IoT in service context as 'a dynamic end to end information network seamlessly linking physical and cyber space by which data from objects are connected, interacting and processed to enable people, objects and systems turning data into useful information and valued services to users'. They argued that the capacity and smart characteristics of IoT enabled service innovation by (1) enlarging the data collection from human-centred to the human–nonhuman network and (2) offering smart services realised by telematics as well as automation from varied embedded networked sensors. However, something like guidance or methodology for realising IoT service is not mentioned. Miorandi et al. (2012) discussed how the findings about design of markets and pricing schemes in traditional ICT fields could be transferred to IoT to provide IoT service. The objective of this paper is to provide general ideas based on experience in related markets. Xing, Wang, and Li (2010) proposed service categories of IoT according to technical features. They are identity-related services, information aggregation services, collaborative-aware services and ubiquitous services. Haller, Karnouskos, and Schroth (2009) provided further application examples for these services. Ma (2011) introduced their project of 'research on the architecture of IoT', which mainly focuses on service adaption in the dynamic system environment. Xu (2012) concentrated on creating dynamic infrastructures to support the integration of the data into the Web and provide unified access to such data on service and application levels. Bohli, Sorge, and Westhoff (2009) presented the design of a comprehensive description ontology for knowledge representation in the domain of IoT and briefly discussed how it could be used to support tasks. We once introduced the idea of cognitive and proactive IoT service as well as a user-centric IoT service architecture (Shang, Zhang, and Chen 2012). Gigli and Koo (2011) proposed an IoT service platform that mainly supports the mobile features of IoT terminal devices.

Although most of the published studies on IoT are more or less related to the service issues, their research branches are various. Any potential epoch-making technologies will suffer a development path from the laboratory to economic sectors and to human daily life. Now IoT is considered as the next-generation network and is capable of providing advanced services. Currently, many different kinds of information services are provided based on the facility of the Internet. A fledged and steady running service must rely on the scientific service design rules, models or theories (Caswell and Ramanathan 2000; Fischer, Gall, and Hauswirth 2002; Tien 2011). These service design guidelines are partly determined by the features of underlying supporting technology. So what kind of service IoT can provide largely depends on the technical features it owned. The rest of this paper will present our design theories and models for IoT service based on its technique features.

3. Design theories and reference architecture for IoT service

As discussed above and shown in Figure 2, in order to establish a well-running IoT service system, the research problem needs address the purpose of establishing a service system or what kind of service will be needed. For instance, an IoT service system that mainly provides video monitoring is technically different from that of collecting environment temperature. Such a difference may result in a different system design. The most significant character of IoT is the possible access of every 'thing'. Following this, issues like how to provide such service and how to make the service system extensible are arising. The above three issues are basic questions that deserve to be considered before establishing an IoT service system. As for the service and system optimisation, running with high efficiency is the point we focus on. From this section, we study the above issues from both the methodology level and the application level.

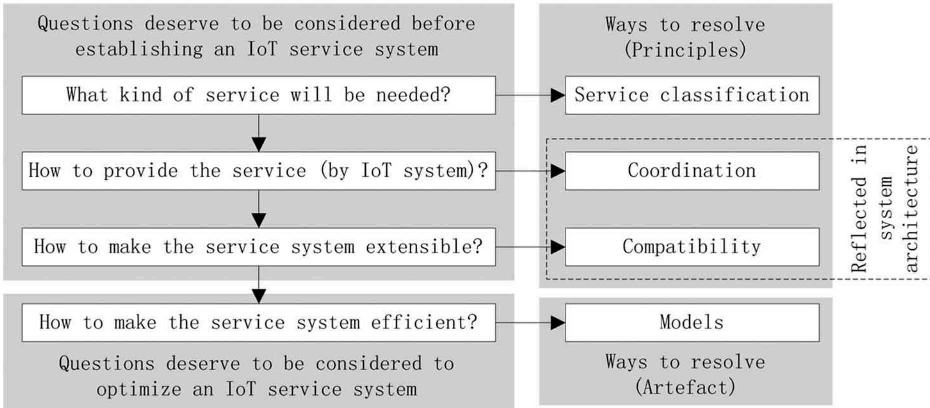

Figure 2. Research motivation and content.

3.1. *Design theories*

Past studies have been rarely carried out about the design theory for establishing an IoT system, especially in an enterprise context. As discussed earlier, IoT is not a specific technique but a technology of system integration. Thus, based on our former researches (Shang, Zhang, and Chen 2011; Shang et al. 2011; Shang, Zhang, and Chen 2012), an issue that needs to be addressed is how to combine the enabling technologies into a whole well-performed system. Although IoT service system is relatively new, some basic principles and procedures used in traditional information system, such as the business process analysis, still work. We consider service classification, coordination and compatibility as the three most important issues different from that of a traditional information system in the stage of system design.

3.1.1. *Service classification*

Classifying services is a vital important issue for Quality of Service (QoS) management in all kinds of networks for it directly concerns the network management and optimisation strategy. Traditionally, researches on QoS have always practically aimed at improving the network performance. Many researches imply the hypothesis that if network works well with high physical performance, the QoS will meet the expectation. However, this underlying assumption is problematic. For instance, it is intuitively recognised that the faster the network speed is, the better the user will enjoy when watching videos online. Actually, if the delay of data transmission is limited in a proper time, which can guarantee the video is played smoothly, the user will never mind how much time it has buffered in advance. Besides, limiting the buffer in a proper size will also help save the resource of network bandwidth.

IoT is a fusion environment; it blurs the boundary between the physical world and the human world, which is different from that of the Internet. Thus it allows more chances for IoT to provide advanced services for individual life or manufacturing, not only the traditional ones like searching, charting, mailing, watching videos and so on. The advanced service in IoT is the fusion of a serious system of services while the traditional service in the Internet is mainly request-response-based service. Under this background, it is necessary to value the service quality by the user's satisfaction, which can be reflected through the service's utility for user in IoT. In reality, service classification can be made based on different dimensions, such as being time tolerated or not, bandwidth requirement, precise extent and so on. Proper service classification can aid in choosing a strategy for system design and management, which will significantly help improve the service utility.

To obtain a user-satisfied IoT service, we need to analyse what kind of service the users are looking for in a certain context. From the view of system and service design, it means classifying service type and the corresponding requirement on service resource. As for providing context-based services, service classification is still the premise to establish a mapping relationship between context and service.

3.1.2. *Coordination*

From the perceptive of networks, IoT is a mixed network system. Coordination is pertinent with the ability of 'things' working together with different kinds of networks and devices.

In traditional network applications, user gives order initiatively, and then the networks transmit the order to others or actuators to perform the corresponding response. In an IoT system, a similar operation can be realised automatically by the sensors or tag readers. Thus, the system can access these data automatically, perform analysis, make decision and carry out proper action without the interference of the user.

Ning and Wang (2011) proposed a mankind-neural-system like IoT architecture and tried to show the significance of interconnection and intra-connection and the compatibility in an IoT system. Actually, the neural system is the most important part of the human body that coordinates the voluntary and involuntary actions and transmits signals between different parts of the body. So in fact, what underlies the authors' idea is coordination. De et al. (2012) regard an IoT system must be controlled by a 'management and centralised data centre', which is similar to the human brain. However, more attention and idea on the control of IoT system should be developed regarding the unconditioned nerves reflex in a human nervous system. The biological role of unconditioned reflexes, which serve as the foundation for the rest of the nervous activity of the organism, is an adaptation of the behaviour of an animal of a given species to the usual, constant conditions of its environment. Namely, the unconditioned reflex doesn't need the 'thinking' process. Traditional view of a smart system is that with the ability of 'thinking', but from the human neural system, we know that unthinking is a kind of born smart. Now the technology makes IoT have the ability to realise unthinking smart by direct sensing and automatic actuating without the user being involved. So, unconditioned reflex is an important factor to be considered in the design of an IoT system, which is one aspect of coordination.

As mentioned above, from a user-centred view, using service utility to evaluate IoT efficiency is better than the network performance index. As a consequence, in IoT, designing a possible coordination among the devices and networks so as to realise the whole system is optimum, thereby reflecting the service utility, is of significance.

3.1.3. *Compatibility*

What make IoT exciting to people is the possibility of ubiquitous connection of all kinds of things and devices via network. Effective and extensible communication between these networks and devices is the technical basis for realising more exciting IoT applications. Although some already-existing technologies like gateway and middleware can support heterogeneous connection, IoT proposes a much greater challenge than that of traditional networks. For one thing, many devices in IoT are energy constrained and non-reusable, such as sensor nodes deployed in the wild. These devices are so light that they cannot keep continuous protocol conversion, which is easy for Personal Computer (PC) in traditional networks. For another, IoT is a mixed-network format rather than a specific network type, and it is impossible for one protocol to support the entire IoT in reality. In such a situation, making the protocol extensible is an optimal resolution for networks in IoT.

Although IP has been the most widely used standard for traditional networks, minor distinctions still exist in practice. 'Narrow waist' is the way to deal with these distinctions in the Internet, which represents a common service that permits a wide variety of uses above and a range of implementations below. Thus the Internet can accommodate, even encourage, a vast degree of heterogeneity and diversity in both applications and underlying technologies (Wang et al. 2012). Internet is the most important and ideal inter-media network for different networks in IoT, so the way the Internet works is worth considering to realise an extensible IoT. Besides, the deployment of IP in WSN has been proven effective and a huge amount of IPv6 (IP version 6) address space provides the possibility of identification of every object in the world. WSN is an important DCN, moreover, IP-based WSN protocol is helpful in establishing a seamless connection between WSN and the Internet (Shang, Zhang, and Chu 2013; Shang, Zhang, and Li 2013; Yuan et al. 2013). In order to obtain extensible IoT networks, we recommend adopting an IP-based or simplified IP protocol in network design. Thus, the networks in IoT will have a strong ability to access the Internet without heavy protocol conversion and also can provide easy extensible resolution for heterogeneous networks.

3.2. *Reference architecture for IoT service*

Based on the discussion above, we propose a general reference architecture for IoT service as shown in Figure 3.

This is a service-oriented view, and we classify it into conditional service and unconditional service (Shang, Zhang, and Chen 2012). The idea of this division derives from inspiration of the human nervous system. Unconditional service refers to the service with simple and fixed rules, which does not require a reasoning process, such as a basic alarming service. Conditional service is designed to provide users information with advanced analysis and reasoning, it is necessary to be able to study and evolve according to the need from practice. These two kinds of services have to be linked together by some trigger and coordinating algorithms. We list some basic rules in Figure 3, which are Object Identification (OI), Service Discovery (SD), Service Coordination (SC) and Service Evolution (SE). OI enables the system to uniquely identify an object or a device involved in the service. It also manages the switch in and out of objects and devices in the system. SD is the component for discovering service opportunities, which works on the basis of a user's profile and service context. SC coordinates different services to work together. SE plays the role of SE by feedback and study after enough rounds of services. The service supporting the base works only when conditional service happens. The carrier of this base can be knowledge base, big data analysing tolls or cloud computing platform. Service unit is a functional service

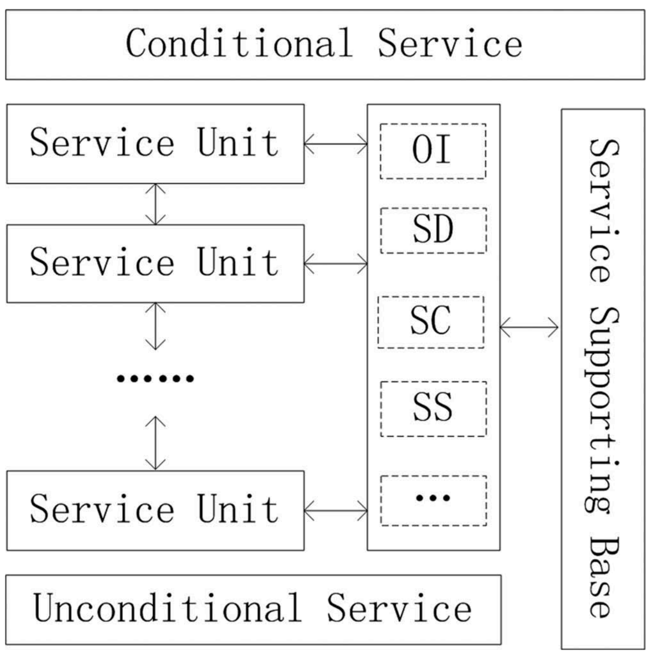

Figure 3. Reference architecture for IoT service.

component, and every service unit is relatively independent. If considering the IoT system as a human, the service unit can be seen like the nose, eyes, hands or other human organs, while the supporting base can be seen as the brain.

This reference architecture is a general model that reflects our ideas of IoT service. In Section 6, we will design a cold chain system based on the reference architecture.

4. Utility model for IoT service

4.1. *Network utility maximisation model*

Following the IoT service design theories, a utility model is proposed in this section. The model aims at optimising resource allocation in the process of service providing.

Kelly, Maulloo, and Tan (1998) first proposed the idea and model about Network Utility Maximisation (NUM), which has been widely used. NUM is the problem of maximising the total utility $\left(\sum_{r\in R} U_r(x_r)\right)$ over the source rates (x_r), subject to linear constraints $Ax \leq C$ for all links:

$$\max \sum_{r\in R} U_r(x_r) \tag{1}$$

subject to

$$Ax \leq C$$

over

$$x \geq 0$$

Based on NUM, much improved work has been done (Low and Lapsely 1999; Chiang 2005; Chiang et al. 2007; Long et al. 2008; Hong and Luo 2013), while all of these researches focus on the resource allocation of network links in wired networks.

4.2. *Utility model in IoT service*

4.2.1. *Problem statement and model*

The final purpose of a utility model for most practices is to describe and improve the satisfaction a user/consumer can acquire under a certain (limited) level of service ability. In NUM, the resources of service are the network links. Finding the optimal allocation scheme on limited links to allow the user have the highest using experience is the target issue.

An important premise of resource allocation is the unified measuring standard for resources. Bandwidth is the most widely used measuring parameter for network links, which is also the variable to be determined in NUM. In IoT, however, accessing devices are the most typical resources different from those of traditional networks and the network is heterogeneous. So considering the features of IoT, bandwidth is inadequate to be directly adopted as the optimising parameter from the viewpoint of IoT service.

In this section, we propose a utility model for IoT service by following NUM. The current model is only applicable to the case of IoT subnet, which contains the same type of devices. In order to measure the working/service-providing ability of the devices (e.g., sensor nodes, RFID reader, GPS, etc.), we choose effective numbers of request-response frequency per second (r/s) as the evaluation unit, which is radically determined by the device's computing ability. The reason for choosing this unit lies in the following: (1) it indicates the device's working/service-providing capacity and efficiency intuitively; (2) it implies the device's maximum working/service-providing capacity in a certain period; (3) it provides the possibility of charging for IoT service from the user by the IoT service operator; and (4) it shields the physical parameter difference when different devices exist in the same network, which is easy for designing a service system with well-matched service ability.

The general utility model is given as follows:

$$\max \sum_{s} U_s \left(\sum_{d} x_{sd} \right) \tag{2}$$

subject to

$$\sum_{s} x_{sd} \leq C_d;$$

$$\sum_{d} x_{sd} \leq \frac{A_s}{T_s}$$

over

$$x_{sd} \geq 0,$$

where x_{sd} represents the response from 'device d' to 'service s' that the system can provide; C_d is the maximum request-response capacity of 'device d'; A_s refers to the total amount of request that 'service s' needs; and T_s is the service time that distributes to service s. Note that x_{sd} is the variable, and C_d, A_s, and T_s are given.

The objective function aims at making the services reach a maximum utility for the whole IoT system. Constraint $\sum\limits_{s} x_{sd} \leq C_d$ makes sure the capacity of the system can satisfy the total requests of all services. And $\sum\limits_{d} x_{sd} \leq \frac{A_s}{T_s}$ constrains the service efficiency under the context of A_s and T_s.

Compared with the NUM model, problem (2) adds the constraint $\sum\limits_{d} x_{sd} \leq \frac{A_s}{T_s}$, which actually indicates the meaning of variety x_{sd}. Also, x_{sd} can be replaced by other parameters such as working time or energy consumption.

As mentioned above, an IoT system may contain various kinds of devices that play different functions. Model (2) is adaptable for a system that contains one type of device, such as a sensor network. In case of an IoT system with different devices, we formulate the model as follows:

$$\max \sum_{t} \sum_{s_t} U_{s_t} \left(\sum_{d_t} x_{s_t d_t} \right) \tag{3}$$

subject to

$$\sum_{s_t} x_{s_t d_t} \leq C_{d_t}$$

$$\sum_{d_t} x_{s_t d_t} \leq \frac{A_{s_t}}{T_{s_t}}$$

over

$$x_{s_t d_t} \geq 0,$$

where $x_{s_t d_t}$ represents the response that the system can provide to service request s from device d for the service type t. Service type is the service that is provided by a specific device, such as sensor service, RFID service, and so on. Similarly, C_{d_t}, A_{s_t} and T_{s_t} are all variables for a specific service type. Service type t is a hard constraint, which means if a user requests service from some specific device, the system should provide such a service, so we treat it as the subscript of service attribute rather than the normal constraint.

4.2.2. *Model analysis*

In order to present a clear description, we ignore the case of different service types, and the following discussion is based on model (2). Note that model (2) is a convex optimisation problem, which will have global optimal solution theoretically, and there are already several ways to solve this model, such as CVX – a MATLAB-based modelling system for convex optimisation. So the resolution of the model is not the emphasis in this paper. However, in order to reveal some potential information in this model, we analyse by using the Lagrange function here, which is a typical method to resolve the convex optimisation problem.

The Lagrange equation is formulated as Equation (4), where λ_d and v_s are non-negative Lagrange multipliers, and μ and η are non-negative stack variables. In this equation, λ_d can be seen as the user's payment for every resource request, and v_s represents the price of time that device occupies.

$$L(x,\lambda,v) = \sum_s U_s\left(\sum_d x_{sd}\right) + \sum_d \lambda_d\left(C_d - \sum_s x_{sd} - \mu\right) + \sum_s v_s\left(\frac{A_s}{T_s} - \sum_d x_{sd} - \eta\right) \tag{4}$$

The optimal solution of this model can be acquired by finding the optimal solution of its dual problem. The dual problem is formulated as

$$\min D(\lambda,\gamma) \tag{5}$$

subject to

$$\lambda \geq 0$$
$$\gamma \geq 0,$$

where $D(\lambda,\gamma) = \max_x L(x,\lambda,v)$.

Gradient method is an option to solve the above-mentioned problem (Bertsekas 1999). Before getting the gradient descent, we need to know $\frac{\partial D}{\partial \mathbf{u}}$, where $\mathbf{u} = [\boldsymbol{\lambda},\mathbf{v}]^{\mathrm{T}}$. After this, following the iterative Equations (6) and (7), we can acquire the following solution:

$$\lambda_d(t+1) = \lambda_d(t) + \beta(t)\frac{\partial D}{\partial \lambda} \tag{6}$$

$$v_s(t+1) = v_d(t) + \beta(t)\frac{\partial D}{\partial \gamma} \tag{7}$$

$U_s(z_s) = \begin{cases} \log(z_s+1), v=0 \\ \frac{-1}{(z_s+1)^v}, v \neq 0 \end{cases}$ where $Z_s = \sum_s x_{sd}$ is an available utility function proposed by Lee, Mazumdar, and Shroff (2005) and Kunniyur and Srikant (2003).

Assuming x_{sd} is the feasible solution of problem (2), Equation (4) can be transferred into

$$L(x,\lambda,v) = \left[\sum_s U_s\left(\sum_d x_{sd}\right) - \sum_s v_s \sum_d x_{sd} - \eta\right] + \left[\sum_d\sum_s v_s\frac{A_s}{T_s} - \sum_d\sum_s \lambda_d x_{sd}\right] + \left[\sum_d \lambda_d C_d - \mu\right] \tag{8}$$

In Equation (8), $\sum_s U_s\left(\sum_d x_{sd}\right)$ is the users' utility, and $\sum_s v_s \sum_d x_{sd}$ is the cost of running the service. Thus, $\left[\sum_s U_s\left(\sum_d x_{sd}\right) - \sum_s v_s \sum_d x_{sd}\right]$ indicates the difference between user's utility and the service cost, namely the profit the user actually obtains. $\sum_d\sum_s v_s\frac{A_s}{T_s}$ shows the system cost to satisfy the current service requests, and $\sum_d\sum_s \lambda_d x_{sd}$ is the user's payment for the service the system

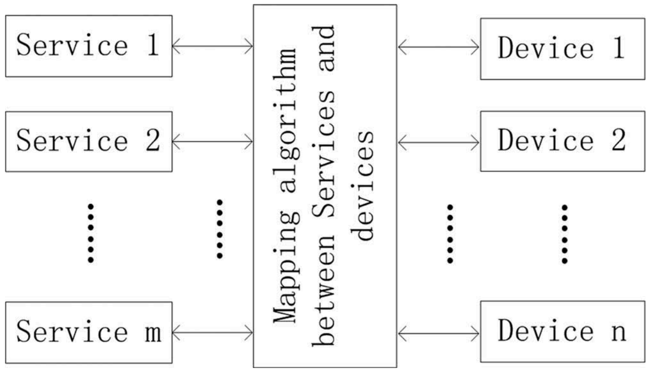

Figure 4. Relationship between services and devices.

provides. So $\left[\sum_d \sum_s v_s \frac{A_s}{T_s} - \sum_d \sum_s \lambda_d x_{sd}\right]$ indicates the difference between the system service cost and the operator's income. However, $\sum_d \lambda_d C_d$ is the maximum income of the system. Obviously, the Lagrange equation can help in the economic analysis and price decision on IoT service based on the service and request information.

In the application, the utility model acts as a mapping algorithm between services and devices to distribute the corresponding resources to service requests to maximise the system's total utility. Figure 4 shows such a relationship between services and devices.

5. IoT service in cold chain visibility – an application illustration

Following the design theory and utility model for IoT service, in this section we illustrate how a cold chain visibility platform is designed and established with the consideration of IoT service issues.

Specifically, supply chain visibility includes the level of data and image. In the data level, what supports visibility is the real-time data, such as temperature, humidity and vibrations. Image-level visibility is responsible for displaying the pictures and videos. This cold chain visibility platform is a part of a food supply chain management system that aims at managing and monitoring the whole process of cold food production and transportation. We focus on the image level of the cold chain visibility platform.

5.1. *System objective*

This cold chain visibility platform plays the role of improving the food safety by monitoring the whole food transportation process. The safety here has two meanings – one is to ensure the food is kept in a qualified storage environment during transportation. The other is to guarantee the workers process the food following the operation standard. Meanwhile, the data generated and stored by the visibility platform is helpful for food traceability and supervision. Accordingly, this platform covers the stages of food process, storage, transportation and sale. The platform user ranges from manufacturer to distributor, retailer and administrative department.

5.2. *System design*

Although some design work has been carried out in this project, more analysis will be provided by following the IoT service design theories in this part.

5.2.1. *Service analysis*

5.2.1.1. *Service classification.* Scientific service classification can help us make an appropriate strategy on system design and management. This platform plans to realise the visibility on the image level, which is time-sensitive. The visibility here refers to (1) the real-time video surveillance and (2) the real-time food condition/environment/location. Figure 5 shows the characteristic function image of the utility for the above-mentioned two cases.

Figure 5(a) describes the utility of non-interactive service, which is a concave function that passes the origin point. In this case, the service utility grows with the increase of service quality (such as the network condition). The service of acquiring real-time food condition/environment/location belongs to this type. Figure 5(b) shows the utility curve of interactive service, which is piecewise. Only when the network condition reaches a certain level that makes the user receive information in a tolerable waiting time, this interactive activity may happen. Otherwise, the user will give up the service due to unexpected waiting time. The service that provides real-time video surveillance is such a kind of service. For instance, if the real-time video is not smooth enough and the user can hardly tolerate the delay of the frames, the service utility is zero. Only when the service condition is better than the tolerance point can the service utility generate.

The service classification directly concerns the choice of utility function. This supply chain visibility chain platform should provide both interactive and non-interactive services. Transpiration video monitoring is an interactive service while sensor data transmission is a non-interactive service. Thus at least two different utility functions are needed in this platform according to the business features.

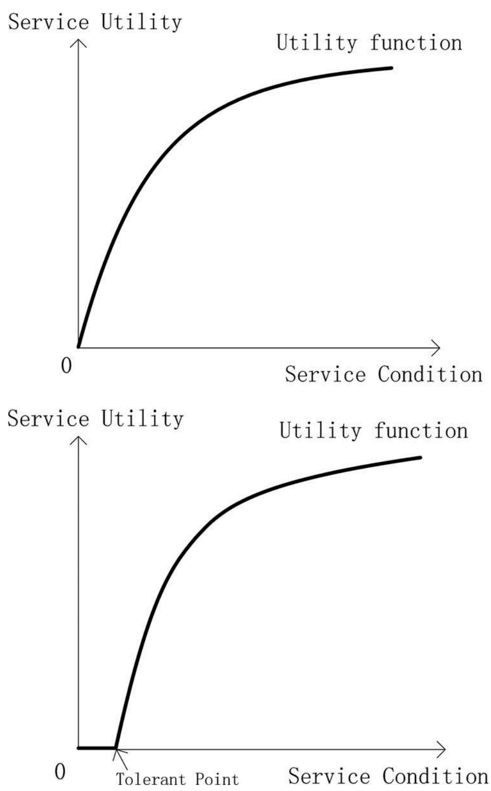

Figure 5. Service utility functions in the platform. (a) Utility function of interactive service. (b) Utility function of non-interactive service.

5.2.1.2. *Coordination and compatibility.* Devices like camera, RFID reader and writer, temperature sensor and humidity sensor work as the nervous endings of this platform. Based on these devices, conditional and unconditional reflexes are needed to be properly designed.

Basically, in this platform, unconditional reflex actions can act under relatively fixed rules, such as automatic alarming and automatic adjustment, while conditional reflex has to work with the decision support system or other business control systems on the basis of real-time data. Accordingly, the corresponding interface for this platform is required due to the involvement of an external design support system.

Compatibility is of significance for service adaptability. From the perspective of the hardware, IoT is a huge system that should have the ability to accept the access of different kinds of devices and terminals. Thus, in the system design process, we need to consider realising extensible protocol architecture so as to shield the hardware diversity to the maximum. As discussed, IP-based network service is an ideal resolution and suitable for this platform, which makes it easier for system and service expending.

5.2.2. *Business process and architecture illustration*

The general business process of the cold chain visibility platform is shown in Figure 6.

Initially, the processed food is inspected and the qualified ones will be cooling down. After the temperature reached the delivery condition, the cold food will be loaded and delivered to markets or other storages. During the whole period including the transportation process, RFID reader, sensors, GPS/Beidou and video system will keep collecting necessary information and videos to ensure the food is being kept in qualified environment. Besides, the actuators will carry out corresponding action according to the change of real-time context information. In Figure 6, dotted line boxes denote the unconditional reflex-control circle.

The whole architecture of cold chain visibility platform, which includes external systems, such as already-existing Enterprise Information System (EIS), is shown in Figure 7. The utility control platform is the place where utility model can be deployed to control the corresponding IoT service resource allocation.

5.3. *Utility model to apply in cold storage monitoring*

System optimisation is an important issue when establishing a real system. For example, we select the module of cold storage as the application scenario that adopts WSN monitoring and control as the service facility.

Suppose the cold storage has 50 monitoring areas, each of them is deployed with seven sensor nodes that sense the temperature. The function of each node in the same area is alternative. In one area, each sensor node may have ongoing missions when a new service request arrives, so the sensor nodes may have different available service resources at the same time. In the model we propose, assume 10 service requests are generated in one area. The purpose of optimisation is to maximise the service utility by allocating limited service resources, which is described as follows:

$$\max \sum_{s=1}^{10} U_s\left(\sum_{d=1}^{7} r_{sd}x_{sd}\right) \tag{9}$$

subject to

$$\sum_{s=1}^{10} r_{sd}x_{sd} \leq C_d; d = 1, 2, 3, \ldots, 7$$

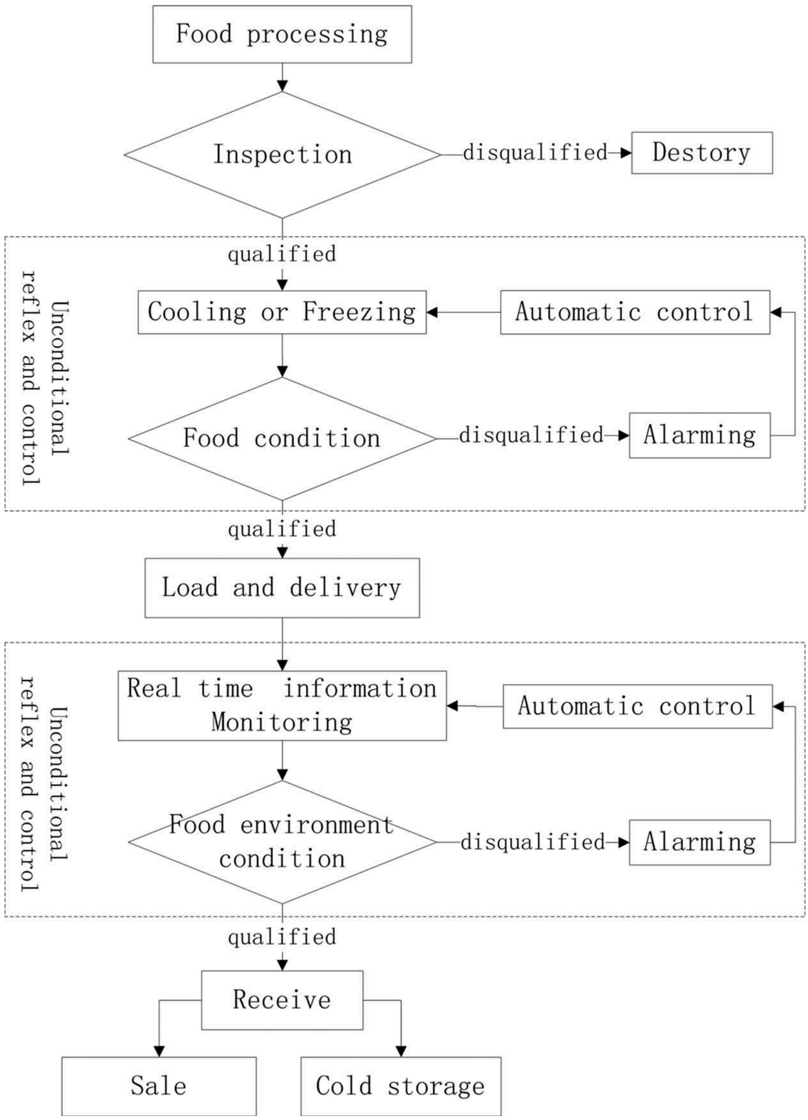

Figure 6. The general business process of cold chain visibility platform.

$$\sum_{d=1}^{7} r_{sd}x_{sd} \leq \frac{A_s}{T_s}; s = 1, 2, 3, \ldots, 10$$

over

$$x_{sd} \geq 0; \quad s = 1, 2, 3, \ldots, 10; \quad d = 1, 2, 3, \ldots, 7,$$

where r_{sd} denotes whether device d is available ($r_{sd} = 1$) or not ($r_{sd} = 0$) to provide service s. And the rest of the notations have the same meaning as those in problem (2).

Obviously, the service here is interactive service. According to the analysis above, we use the continuous function $U_s = \log\left[\sum_{d=1}^{7}(x_{sd}+1)\right]$ to describe the utility, and the input factors are C_d, v_s, λ_d, r_{sd}, A_s and T_s. (s = 1,2,. . .,10; d = 1,2,. . .,7)

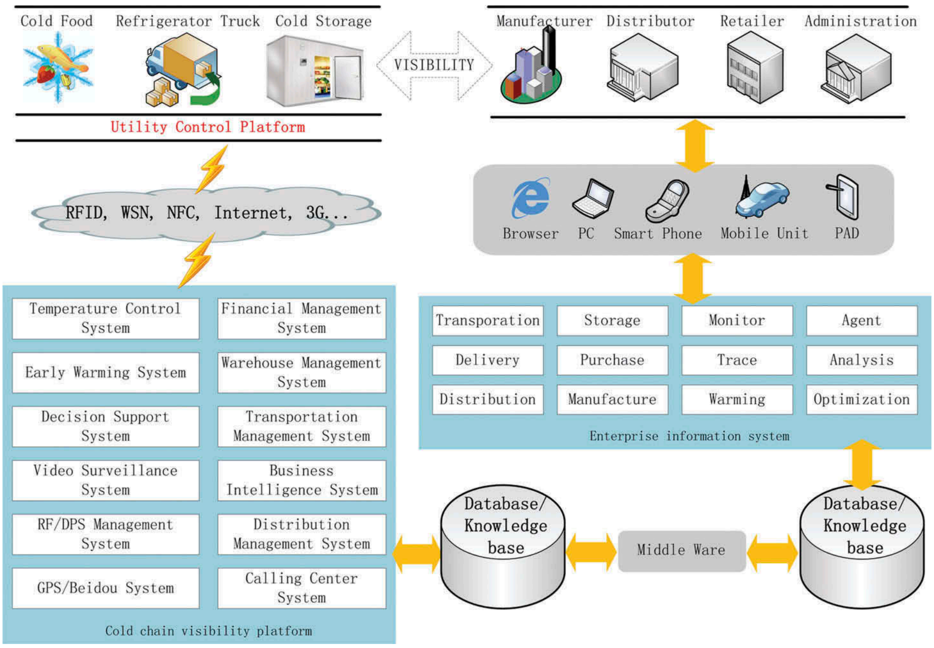

Figure 7. Cold chain visibility platform and enterprise information system.

As an example, we give the solving steps based on problem (3) as follows:

Step 1: Obtain the simplified Lagrange function of Equation (9):

$$L(x,\lambda,v) = \sum_{s=1}^{10}\left[U_s\left(\sum_{d=1}^{7} r_{sd}x_{sd}\right) - v_s\sum_{d=1}^{7} r_{sd}x_{sd}\right] + \sum_{d=1}^{7}\sum_{s=1}^{10}\left[v_s\frac{A_s}{T_s} - \lambda_d r_{sd}x_{sd}\right] + \sum_{d=1}^{7}\lambda_d C_d \tag{10}$$

Based on Equation (10), it can obtain some relationship between the service cost and price as described in Section 4.2.2.

Step 2: Obtain the starting point of iteration as: $\mathbf{X}^{(1)} = \mathbf{0}$.

Step 3: Obtain the gradient direction of $\mathbf{g}$:

$$\mathbf{g}^{(\mathbf{k})} = \left[\frac{\partial L}{\partial \lambda}, \frac{\partial L}{\partial \gamma}\right]^{\mathrm{T}} = \left[\sum_{d=1}^{7} C_d - \sum_{d=1}^{7}\sum_{s=1}^{10} r_{sd}x^{(k)}{}_{sd}, \sum_{d=1}^{7}\sum_{s=1}^{10}\frac{A_s}{T_s} - \sum_{s=1}^{10}\sum_{d=1}^{7} r_{sd}x^{(k)}{}_{sd}\right]^{\mathrm{T}} \tag{11}$$

Step 4: Obtain the step factor $\xi^{(k)}$ ($\xi^{(k)} \geq 0$), which satisfies condition (12), and if $\xi^{(k)} < 0$, let $\xi^{(k)} = \xi^{(k-1)}$.

$$\min(\mathrm{X}^{(k)} + \xi^{(k)}\mathrm{g}^{(k)}) \tag{12}$$

Step 5: Obtain $\mathbf{X}^{(k+1)}$ by the following equation:

$$\mathbf{X}^{(k+1)} = \mathbf{X}^{(k)} + \xi^{(k)}\mathbf{g}^{(k)} \tag{13}$$

Step 6: Check the following condition:

If $\mathbf{X}^{(k+1)} - \mathbf{X}^{(k)} < \boldsymbol{\varepsilon}$, stop the iteration process; otherwise, jump to step (3).

Output: The optimal solution $\mathbf{X}^{(k+1)}$.

6. Conclusions

IoT is not a specific network format, but rather a systemic design idea that enables all kinds of devices and systems to work together, getting real-time information, context information as well as feedback from other working systems and finally realising the status of coordinate working. In this paper, we use the term 'IoT service' to generalise the whole system functions that an IoT system can provide.

By reviewing the vision of IoT and traditional information service, we conclude the characters of modern IoT service can be interpreted as the human nervous system. It consists of conditional service and unconditioned service, which can help realise smarter and efficient information service than traditional ones. According to the analysis on IoT service, three main principles – service classification, coordination and compatibility – are proposed to help design an IoT service system. Based on the design theory, for a deeper level, we worked out the utility model for IoT service, which can be used for resource allocation and making price strategy for user and IoT facility operator in the stage of IoT service running. In the end of the paper, we select an ongoing project as the application scenario, illustrate how the IoT service is considered and formulate the system design process in the real enterprise context.

Although IoT service is a relatively new concept compared with that of traditional networks, it is closely related to the deployment of IoT and its enabling technologies. Only scientific design theory as well as service optimisation algorithms working together can help establish a more efficient IoT information system and make IoT change from a pure technique product to service-supporting technology. Future research on IoT service optimisation could further investigate the utility model that adapts the whole IoT service system and realising the resource allocation among heterogeneous subnets of the IoT service system.

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