Ma HD. Internet of things: Objectives and scientific challenges. JOURNAL OF COMPUTER SCIENCE AND TECHNOLOGY 26(6): 919–924 Nov. 2011. DOI 10.1007/s11390-011-1189-5

Internet of Things: Objectives and Scientific Challenges

Hua-Dong Ma (马华东), *Member*, *CCF*, *ACM*, *IEEE*

Beijing Key Lab of Intelligent Telecommunications Software and Multimedia,
School of Computer Science, Beijing University of Posts and Telecommunications, Beijing 100876, China

E-mail: mhd@bupt.edu.cn

Received July 18, 2011; revised September 5, 2011.

Abstract The Internet of Things (IoT) is aimed at enabling the interconnection and integration of the physical world and the cyber space. It represents the trend of future networking, and leads the third wave of the IT industry revolution. In this article, we first introduce some background and related technologies of IoT and discuss the concepts and objectives of IoT. Then, we present the challenges and key scientific problems involved in IoT development. Moreover, we introduce the current research project supported by the National Basic Research Program of China (973 Program). Finally, we outline future research directions.

Keywords Internet of things, architecture, data exchange, information integration, service delivery

1 Background

Information networks have been used in every aspect of daily life to provide interconnection among many devices, such as entertainment devices, transportation vehicles, communication equipments, household appliances, aircrafts, personal computers and all kinds of sensors. Information networks have become an integral part of people's daily lives. The design and implementation of new types of networks have been the core research topics since the beginning of this century. For instance, the National Science Foundation (NSF) of the USA had started two research projects concerning the Internet since 2005: one is *Global Environment for Network Innovations* (GENI)[1] and the other is *Future INternet Design* (FIND)[2]. Being a networking experimental environment, the motivation of GENI is to improve the architecture and services of the future Internet, to encourage researchers to propose revolutionary concepts and techniques for the future Internet. FIND is a long-term project under the Networking Technology and Systems (NeTS) research program of NSF. The motivation of FIND is to build a brand new network starting with the design of drafts in order to satisfy the requirements for the coming 15 years. Another project is *Future Internet Research and Experimentation* (FIRE)[3] under the European Seventh Framework Programme (FP7). The FIRE is proposed by European Union at the beginning of 2007, and its motivation is to create a multidisciplinary research environment for investigating and experimentally validating highly innovative and revolutionary ideas for new networking and service paradigms, thus further improve the research of architectures, protocols, management mechanisms, and service prototypes of the future Internet. At the same time, other countries, such as Korea and Japan, have started research programs about the future Internet as well. For instance, Korea started *the Future Internet Forum* (FIF)[4] in 2006, which aims to provide an opportunity to review the forefront information and knowledge on the timely subject of new Internet architecture and related issues. In order to discuss the concepts for new generation network, technical issues and measures to promote its realization, Japan established *the New Generation Network Promotion Forum* (NWGN)[5] in 2007.

At present, the construction of physical infrastructure is separated from that of information infrastructure such that the computing pattern represented by the Internet has attracted the usage of people into the cyber space. However, current social development requires us to extend computing techniques to the physical space for human survival and development. The Internet of Things (IoT) can enable the interconnection and integration of the physical world and the cyber space; it represents the trend of future networking, and leads the third wave of the IT industry revolution. Currently, the related technologies about IoT have become the

---

Survey

This work is supported by the National Basic Research 973 Program of China under Grant No. 2011CB302701, the National Natural Science Foundation of China under Grant No. 60833009, and the National Natural Science Foundation for Distinguished Young Scientists of China under Grant No. 60925010.

international focus, and they are widely considered as one of the most important infrastructures for promoting economy development and technology innovation. The developed nations have considered the development of IoT as one of the future development strategies and put huge investment into it in order to cultivate new economic growth points. For example, IBM proposed *the Smarter Planet* strategy[6] in Jan., 2009, which obtained positively response from the government of the United States. The European Union published 14 action plans[7] about IoT in June, 2009 to ensure that the European Union will lead the future construction of IoT. In China, Premier Jia-Bao Wen put forward the strategic concept of *Sensing China* in Aug., 2009, and proposed that China should seize the opportunity to develop the key techniques of IoT. China's IoT-related research and development are mainly supported by the National Basic Research Program of China (973 program) for grand strategic basic research projects, the National High Technology Research and Development Program of China (863 program) for technical research and development projects, and National Natural Science Foundation of China for explorative researches.

In this article, after providing some background knowledge of IoT, we discuss the concept and objectives of IoT. Then, we present challenges and key scientific problems involved in IoT development. Moreover, we introduce our research project "*Basic Research on the Architecture of Internet of Things*", supported by the National 973 Program. Finally, we outline future research directions.

2 Concepts and Objectives of IoT

2.1 What is IoT

The initial idea of IoT was proposed by MIT Auto-ID Labs at the end of 1990's[8], which originated from the requirement of logistics. ITU Internet Reports 2005[9] indicated that we are heading towards a "ubiquitous network society", one in which networks and networked devices are omnipresent. In the future, everything from tires to toothbrushes will be in communication range, heralding the dawn of a new era, one in which today's Internet (of data and people) gives way to tomorrow's Internet of Things. The concept of "Things" in IoT has been generalized to ordinary objects at present, and the interconnection technology is also extended to all networking technologies, including RFID (Radio Frequency Identification).

IoT is closely-related to the Internet, mobile communication networks and wireless sensor networks. Comparing IoT with WSNs, Internet, ubiquitous networks and further analysis, we define IoT as follows.

Based on the traditional information carriers including the Internet, telecommunication network and so on, Internet of Things (IoT) *is a network that interconnects ordinary physical objects with the identifiable addresses so that provides intelligent services.*

IoT has three important characteristics.

1) Ordinary objects are *instrumented*. It means that ordinary objects such as cups, tables, screws, foods and automobile tires can be individually addressed by means of being embedded with chip, RFID, bar code and so on.

2) Autonomic terminals are *interconnected*. It means that the instrumented physical objects are connected as autonomic network terminals.

3) Pervasive services are *intelligent*. In such an extensively-interconnected network, letting every object participate in the service flow to make the pervasive service intelligent. For example, the sensor nodes of vehicle-carrying network or human-carrying network can monitor the status of road or the body of driver to obtain real-time information for guiding driving behaviors.

Therefore, IoT is a sophisticated comprehensive inter-disciplinary technology, e.g., encompassing multiple areas such as computer science, communications, microelectronics and sensor technology.

For clarity of discussion, we divide the architecture of IoT system into four layers: object sensing layer, data exchange layer, information integration layer, and application service layer. The four-layer architecture is shown in Fig.1. The object sensing layer handles sensing the physical objects and obtaining data; the data exchange layer handles transparent transmission of data; the information integration layer handles recombination, cleaning and fusion of uncertain information acquired from the networks, and integrates the uncertain information into usable knowledge; the application service layer provides content services for various users.

Application Service Layer
Information Integration Layer
Data Exchange Layer
Object Sensing Layer

Fig.1. Four-layer architecture of IoT.

The traditional Internet generally does not have sensing ability, and only interconnects the intelligent devices. In contrast, the IoT has the additional sensing layer, which reduces the requirements on the capability of devices, and enables the interconnection among the non-intelligent or weakly-intelligent devices. Meanwhile, it brings about many new requirements and challenges to data exchange, information integration and services, as well as the complexity of the network architecture.

Based on this architecture, we need to further study methods and mechanisms for interconnecting a wide variety of heterogeneous networks. The architecture of IoT should be studied from the viewpoint of users, network providers, application developers and service providers, providing the basis for defining a wide variety of interfaces, protocols and standards.

Another concept that is closely related to IoT is Cyber-Physical System (CPS)[10], defined as a system that integrates the 3C: Computation, Communication and Control, and realizes the interaction between the physical world and the cyber world. CPS can provide real-time sensing, dynamic control, information feedback, and other services.

Although both IoT and CPS are aimed at increasing the connection between the cyber space and the physical world by using the information sensing and interactive technology, they have obvious differences: the IoT emphasizes the networking, and is aimed at interconnecting all the things in the physical world, thus it is an open network platform and infrastructure; the CPS emphasizes the information exchange and feedback, where the system should give feedback and control the physical world in addition to sensing the physical world, forming a closed-loop system.

2.2 Objectives of IoT

Compared with the traditional information networks, IoT has three new goals, i.e., more extensive interconnection, more intensive information perception, and more comprehensive intelligent service. They are elaborated as follows.

2.2.1 More Extensive Interconnection

IoT extends the interconnection among the information equipments, such as computer and mobile phone, to the interconnection of all intelligent or non-intelligent physical objects. It has the following outstanding characteristics:

1) Extensiveness in the quantity of devices. The amount of the connected devices will sharply rise from several billions to over hundreds of billions, including a multitude of equipments, sensors, actuators, vehicles, and devices attached with RFID.

2) Extensiveness in the type of devices. Networking devices (networking elements) may be powered by the electronic power directly or by batteries; the computation and communication capacity may be greatly different, e.g., some devices even may not have any computational ability.

3) Extensiveness in the connection mode. The devices may be connected in a wired or wireless mode; the communication could be a single hop or multiple hops; the connection can be strong state routing or statistical weak state routing.

Thus, in such a large-scale heterogeneous network, we must meet the challenge of highly-efficient interconnection of network elements.

The Internet Protocol (IP) is suited for networking devices with stringent requirements[11-12]. For example, the devices should have strong computation and communication capabilities; their runtime operation relies on relatively stable environment, and the route is often based on fixed connections or strong state. On the contrary, IoT needs to connect many devices with weak capabilities (e.g., wireless sensor nodes, RFID) besides the traditional devices; the network may be multi-hop, self-organizing, intermittent and susceptible to influence by harsh environment. Hence it is often a statistical weak-state connection. In such cases, IP cannot be used as the data exchange protocol directly. Recently, novel data transmission and routing techniques have been explored, which are called non-IP protocols, such as Delay-Tolerant Networking (DTN)[13], weak state routing[14], opportunistic routing, location-based routing, and event-based routing. The future IoT must handle the convergence of IP and non-IP protocols. Due to the heterogeneity of network elements and the dynamic application environments, we need to study a variety of networking requirements and the corresponding interconnection models and mechanisms in IoT. New types of dynamic network element addressing models should be studied to ensure the compatibility between network elements with different capabilities, forming the basis for supporting the global network convergence required by large-scale heterogeneous networks and effective data exchange required by local dynamic autonomy.

2.2.2 More Intensive Information Perception

IoT extends the paradigm of traditional single sensors that sense the local environment independently to the new paradigm of collaboration of multi-sensors to achieve the global environment awareness. Sensing information from each single sensor may contain uncertainties in the following aspects:

1) *Non-uniformity.* Data formats for temperature, humidity, audio, video, and other information are different from each other.

2) *Inconsistency.* There is inconsistent information due to the distortion of space-time mapping.

3) *Inaccuracy.* A range of information inaccuracies are often caused by the variety of sampling methods and different capabilities of the sensors.

4) *Discontinuities.* Intermittent information availability is often caused by the dynamic network transmission capacity.

5) *Incomprehensiveness.* Incomplete sensing of information is caused by the limitations of sensors. For example, measuring the forest pollution relying on Carbon Dioxide information only is clearly inadequate.

6) *Incompleteness.* Partial loss of information is caused by dynamic network environment.

Therefore, it is difficult to use the sensor information directly, and the challenge of effective utilization of the uncertain sensory data in IoT must be met.

This kind of uncertain information needs certain representation and further to be integrated in order to fuse them into relatively accurate knowledge. Then, we can understand and control the physical environments in a timely manner. For example, in the coalmine gas-monitoring scenario, it is less enough to judge if there is an explosion based on local information only. The decision should be made based on the distribution of gas density and the situation of gas flow after real-time fusion of multi-point information. Sensing the physical world by using the collaboration of multiple interconnected devices necessitates solving the problem of information exchange among different types of network equipments. Therefore, we must address the difficulties in information representation, performance-cost balance and authorization protection during the interaction process among different networking devices.

2.2.3 More Comprehensive Intelligent Service

Based on the extensive interconnection of ordinary physical objects and the intensive perception of the physical world, IoT can provide comprehensive intelligent services, where physical objects are actively involved in the service process. For example, some networks, like vehicle-carrying networks, human-carrying networks, intelligent transportation networks and environment monitoring networks, can be integrated to provide intelligent services, such as dynamic congestion state, weather condition, environment information, and health condition, thus achieve the harmony of people, vehicles, roads and environment. They also can dynamically change the travel suggestions, and instruct users to travel reasonably and efficiently. However, the environment of IoT is dynamic and the question is how software design can adapt to it in order to provide intelligent services.

These intelligent services call for new software modeling theories, service delivery mechanisms and methods that can adapt to the dynamic environment of IoT. The conventional software development method is suitable to the two-tuple problem domain consisting of user requirements and cyber space, but is less suitable for the system environment with three-tuple problem domain consisting of user requirement, cyber space and physical space, and it is also hard to provide flexible, suitable and more comprehensive intelligent service.

As a new type of network, IoT is characterized by the large-scale heterogeneous network elements, the uncertain sensing information, and the dynamic system environment. These features raise the challenges such as highly-efficient interconnection of large-scale heterogeneous network elements, effective utilization of uncertain sensing information and service delivery in the dynamic system environment. At present, there is still no complete theory guiding us to deal with the above challenges, which seriously constrains the development and application of IoT.

3 Key Scientific Problems in IoT

In order to handle the IoT's challenges in extensive interconnection, information perception and intelligent service, we focus on three key scientific problems as follows.

Problem 1. *Data exchange among large-scale heterogeneous network elements.*

Access to large-scale heterogeneous network elements and massive data exchange among them are the important novel features associated with the wide application of IoT. On the one hand, IoT realizes the interconnection and network convergence by using Internet, telecommunication networks and other networking platforms, and provides information sharing and collaborative service. On the other hand, IoT has a strong requirement of dynamic autonomy in each local tight-coupled region. In order to execute a specific network task, various network elements in each local region self-organize dynamically, realize the interconnection and interoperability, thus to improve the network service efficiency by using the information in the local autonomy region. Therefore, here is a key problem that IoT has to face: how to resolve apparent contradiction between the extra large-scale, heterogeneity and dynamics of IoT system, and the requirement of highly-efficient data exchange. For this reason, the challenge of highly efficient interconnection among large-scale heterogeneous network elements is raised as the first key scientific problem of IoT, that is, data exchange of large-scale heterogeneous network elements in local dynamic autonomy and highly efficient network convergence.

Problem 2. *Effective integration and interaction adaptation of uncertain information.*

IoT intensively senses the physical world through various smart devices, and the sensed information is obviously characterized by a lot of uncertainty. The uncertainty needs certain representation after some in-network processing procedures, such as reorganization, purification and fusion, and the result will be further provided to services. Information fusion among network elements needs to exchange information among network elements according to the "anytime and anywhere" requirement, in order to realize highly efficient information sharing. This leads to another key research problem: how to represent, reorganize and use the sensed information, and resolve the problems of interaction adaptation such as information representation, balance between efficiency and energy, and security protection, in order to provide effective support for the application services. Therefore, the challenge of using the uncertain sensing information effectively is raised as the second key scientific problem, that is, effective integration and interaction adaptation of uncertain information.

Problem 3. *Service adaptation in the dynamic system environment.*

In the dynamic IoT system environment, we need to deal with uncertainties of interactive entity objects, randomness of interactions with environment, and constraints of runtime platform that meets changing requirements. We also need to study novel software developing theories and supporting technologies, give the IoT software system context-awareness and dynamic deployment capability in order to realize the environmental adaptability of IoT services. We further need to build the software architecture, give the IoT software the ability of autonomy and evolution, realize the collaborative among the three tuples of user requirement, information domain and physical domain, and enable the IoT software to adapt to the dynamic environment flexibly to provide intelligent services. Therefore, we need to address new software modeling theories, mechanisms and methods suitable for the IoT environment. Consequently, the challenge of resolving the self-adaptation of the IoT service delivery is raised as the third key scientific problem, that is, service adaptation in the dynamic system environment.

4 Current Research Work

With the support of China's National 973 Program, the project "Basic Research on the Architecture of Internet of Things" is carried out to solve the common basic problems in the research and application of IoT. We will address the essential scientific problems of IoT as follows:

1) *Data exchange among large-scale heterogeneous network elements.* Through modeling the architecture of IoT and the interconnection models of sub-networks, we develop the mechanisms of network convergence and autonomy, present the methods of measuring and evaluating the network, and solve the problem of interconnecting large-scale heterogeneous network elements within the context of local dynamic autonomy and highly-efficient network convergence.

2) *Effective integration and interaction adaptation of uncertain information.* Through building the models of the integration of sensing information, we propose the mechanisms and methods of information presentation, performance-cost balance and security protection during the interaction process among the network elements, and solve the problem of the integration and interaction adaptation of uncertain information.

3) *Service adaptation in the dynamic system environment.* Through building the models and the service platforms of the dynamic system environment, we propose the methods of automatically acquiring and understanding environment information and adaptive problem solving, present the mechanisms of the IoT service delivery, and solve the service adaptation problem in the dynamic system environment.

Based on the above study of scientific problems, we design a platform for verifying our theoretic results, and develop a demonstration application of carbon balance surveillance. The basic idea is to extend our ongoing research project called GreenOrbs (http://www.greenorbs.org/)[15-16] for monitoring the forest environment with wireless sensor networks, and integrate it with vehicle carrying networks, intelligent power-usage networks, 3G mobile networks and the Internet, in order to establish a multi-application verification platform of IoT. One typical application is the detection of carbon balance index. First, the carbon sink data of forest are collected using wireless sensor networks. Second, carbon emission data of vehicles, buildings and factories are obtained in real-time by using vehicle carrying network and intelligent power-usage network, etc. Third, both the carbon sink data and the carbon emission data are sent to the data center where the carbon balance index of a region is computed after intelligent data-processing. Finally, relevant people, enterprises and government agencies receive the resulting index. The research results are expected to be helpful to establish a low-carbon society and achieving decision support for decreasing carbon emission according to the above index.

The research is conducted on the following five topics (see Fig.2): 1) theoretical model of the IoT architecture; 2) mechanism and method of the convergence and autonomy of IoT; 3) theory and method of the information integration and interaction of IoT; 4) mechanism and method of service delivery of IoT; 5) verification platform of IoT and the typical application of carbon balance monitoring. There are nine institutions involved in the project, including Beijing University of Posts and Telecommunications, Institute of Computing Technology of Chinese Academy of Sciences, Tsinghua University, Peking University, Shanghai Jiaotong University, Xi'an Jiaotong University, Beijing University of Technology, Zhejiang Agriculture and Forestry University and The Hong Kong University of Science and Technology.

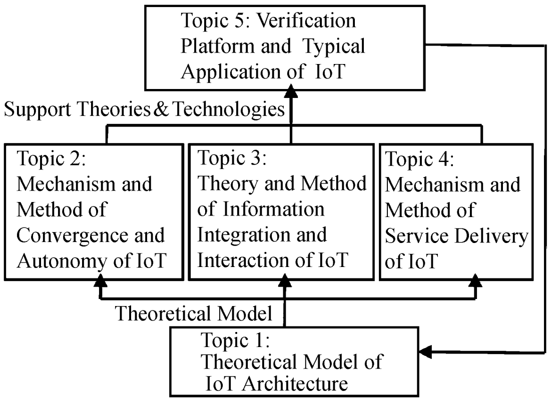

Fig.2. Research framework.

Expected results of this project are as follows: 1) basic theoretical model of IoT architecture for interconnecting heterogeneous network elements, and a framework for the IoT theories and technologies; 2) significant progress in three aspects: network convergence and autonomy, information integration and interaction, as well as service delivery in order to provide basic theories and key technologies for the construction of IoT; 3) an integrated verification platform of IoT for environmental ecology protection, and a typical application of the carbon balance monitoring.

5 Conclusions

The applications of IoT have been further extended to various areas in order to manage people's production and living more accurately and dynamically and improve the relationship between human and environment. This article provided a brief introduction to the main concepts and features of IoT, as well as analyzed the objectives and scientific challenges of IoT technology. It briefly presented the main scientific problems and research contents of the project "Basic Research on the Architecture of Internet of Things", supported by the National 973 Program. In the future, we will try to reveal the basic law of IoT, create the basic model and mechanism of IoT, provide breakthroughs in the key IoT technologies on data exchange, information integration and service delivery, and build the integrated verification platform of IoT and a typical demonstration application. Our work will help form the theoretical framework of IoT, and provide the theoretical foundation for developing large-scale practical IoT systems.

References

[1] Global Environment for Networking Innovation (GENI), http://www.geni.net/, Aug. 2011.

[2] Future INternet Design (FIND), http://www.nets-find.net/, Aug. 2011.

[3] Future Internet Research and Experimentation (FIRE), http://cordis.europa.eu/fp7/ict /fire/, Aug. 2011.

[4] Future Internet Forum (FIF), http://fif.kr/, Aug. 2011.

[5] New Generation Network Promotion Forum (NWGN), http://forum.nwgn.jp/, Aug. 2011.

[6] http://www.ibm.com/smarterplanet/us/en/, Aug. 2011.

[7] Internet of Things — An action plan for Europe, http://ec.europa.eu/information_society/policy/rfid/documents/commiot2009.pdf.

[8] http://www.autoidlabs.org/, Aug. 2011.

[9] International Telecommunication Union. ITU Internet Reports 2005: The Internet of Things, November 2005.

[10] Wolf W. Cyber-physical Systems. *IEEE Computer*, 2009, 42(3): 88-89.

[11] Bush R, Meyer D. Some Internet architectural guidelines and philosophy. RFC 3429, Dec. 2002, http://www.faqs.org/rfcs/rfcs3439.html.

[12] Fall K. A message-switched architecture for challenged Internets. Technical Report, IRB-TR-02-010, Intel Research at Berkeley, Jul. 2002.

[13] Fall K. A delay-tolerant network architecture for challenged Internets. In *Proc. ACM Conf. on Applications, Technologies, Architectures, and Protocols for Computer Communications*, Karlsruhe, Germany, August 25-29, 2003, pp.27-34.

[14] Acer U G, Kalyanaraman S, Abouzeid A A. Weak state routing for large scale dynamic networks. In *Proc. the 13th ACM Int. Conf. Mobile Computing and Networking*, Montreal, Canada, Sept. 9-14, 2007, pp.290-301.

[15] Liu Y, Zhou G, Zhao J, Dai G, Li X Y, Gu M, Ma H, Mo L, He Y, Wang J *et al.* Long-term large-scale sensing in the forest: Recent advances and future directions of GreenOrbs. *Frontiers of Computer Science in China*, 2010, 4(3): 334-338.

[16] Liu Y, He Y, Li M, Wang J, Liu K, Mo L, Dong W, Yang Z, Xi M, Zhao J, Li X Y. Does wireless sensor network scale? A measurement study on GreenOrbs. In *Proc. the 30th IEEE Conference on Computer Communications*, Shanghai, China, April 10-15, 2011, pp.873-881.

Hua-Dong Ma received his Ph.D. degree in computer science from Institute of Computing Technology, Chinese Academy of Sciences in 1995. He is executive dean of School of Computer Science, Beijing University of Posts and Telecommunications (BUPT), China. He is also director of Beijing Key Lab of Intelligent Telecommunications Software and Multimedia, BUPT. He is chief scientist of the project "Basic Research on the Architecture of Internet of Things" supported by the National 973 Program of China. He was awarded National Funds for Distinguished Young Scientists in 2009. His current research focuses on multimedia system and networking, sensor networks and Internet of things. He has published over 100 papers in journals (such as ACM/IEEE Transactions) or conferences (such as IEEE INFOCOM/ICDSC, ACM MM) and 4 books on these fields. He is a member of the CCF, ACM, and IEEE.