A Tutorial on the Internet of Things: From a Heterogeneous Network Integration Perspective

Ke Xu, Yi Qu, and Kun Yang

Abstract

The days when the Internet was the only focus of the information society have already gone, and innovative network paradigms such as IoT, cloud computing, smartphone networks, social networks, and industrial networks are gaining popularity and establishing themselves as indispensable ingredients of the future smart universe. Among them, IoT is the most widespread one, envisioned to involve all things in the world. However, its potential will never be fully explored before the complete formation of cyberspace, where humans, computers, and smart objects are pervasively interconnected. Therefore, one of the most important development trends of IoT is its integration with existing network systems. In this tutorial, we provide a detailed analysis of this issue. In particular, the latest achievements, technical solutions, and influential ongoing projects are described, and possible visions and open challenges are also discussed.

The Internet of Things (IoT) is the network of physical objects embedded with actuators, RFIDs, sensors, software, and connectivity to enable it to interact with manufacturers, operators, and/or other connected devices to reach common goals [1]. It has been a hotspot in both academia and industry since it was proposed by Kevin Ashton in 1999.

As a paradigm that is envisioned to involve all things in the world, IoT can never be an isolated kingdom. It has extensible and compatible features, and is always ready to absorb advantages in every aspect of information domains. Its potential will never be fully explored before the complete formation of cyberspace, where humans, computers, and smart objects are pervasively interconnected. This process can be regarded as the integration of IoT and existing network systems including cloud computing, the Internet, smartphones, and social and industrial networks. Actually, in recent years, the integration of heterogeneous network systems has become a main source of network innovation and has stimulated the proposition of novel interdisciplinary concepts such as the Cloud of Things (CoT), Web of Things (WoT), and Social Internet of Things (SIoT).

With the deepening of integration processes, system boundaries are disappearing, and territories that originally belonged to IoT are becoming shared domains. As shown in Fig. 1, many interdisciplinary territories and overlaps exist between IoT and existing network systems. Generally, IoT expands the scale of the Internet from computers to everything, while the Internet and smartphone networks together provide IoT with fast network backbones. Moreover, leveraging cloud computing, infrastructures and platforms provided by IoT and the Internet are utilized by social, industrial, and smartphone networks to offer human society innovative services.

Specifically, short-range wireless transmission technologies commonly adopted in IoT are unsuitable for long-distance and high-speed connection. Leveraging network infrastructures provided by the Internet and smartphone networks is necessary to interconnect numerous, various, and globally distributed objects. Furthermore, IoT itself cannot store, compute, or analyze massive data collected from trillions of sensors. This weakness is exactly the strength of cloud computing, the computation and storage of which can be regarded as infinite, such that IoT-cloud integration will lead to a win-win situation. Moreover, the combination of IoT and social, industrial, and mobile networks will promote the rise of close human-object interactions, premium products, and various novel applications. All of these services are highly desired, and the integration of heterogeneous network systems will create a better life for mankind.

Recently, a flourish of efforts have been made to study this issue. In [2], the authors focus on the integration between IoT and social networks. And in [3], current research on IoT in enterprises are reviewed in detail. The adoption of IoT systems in smart cities is introduced in [4], while clustering of IoT and cloud computing is presented in [5]. Different from these studies, which only focus on one aspect, in this tutorial, we provide a comprehensive review on the integration of IoT and existing network systems including cloud computing, Internet, smartphone, social, and industrial networks. With particular attention, the latest achievements, technical solutions, and influential ongoing projects are described, and possible visions and open challenges are also discussed. Due to the extremely wide scope of related works, research, and projects, those discussed in this tutorial are representative rather than complete.

Cloud Computing

In practice, most objects are tiny not only in size, but also in capacity. Successfully monitoring the physical world requires a great number of sensors to generate a huge amount of data, which should be stored and processed effectively. Cloud com-

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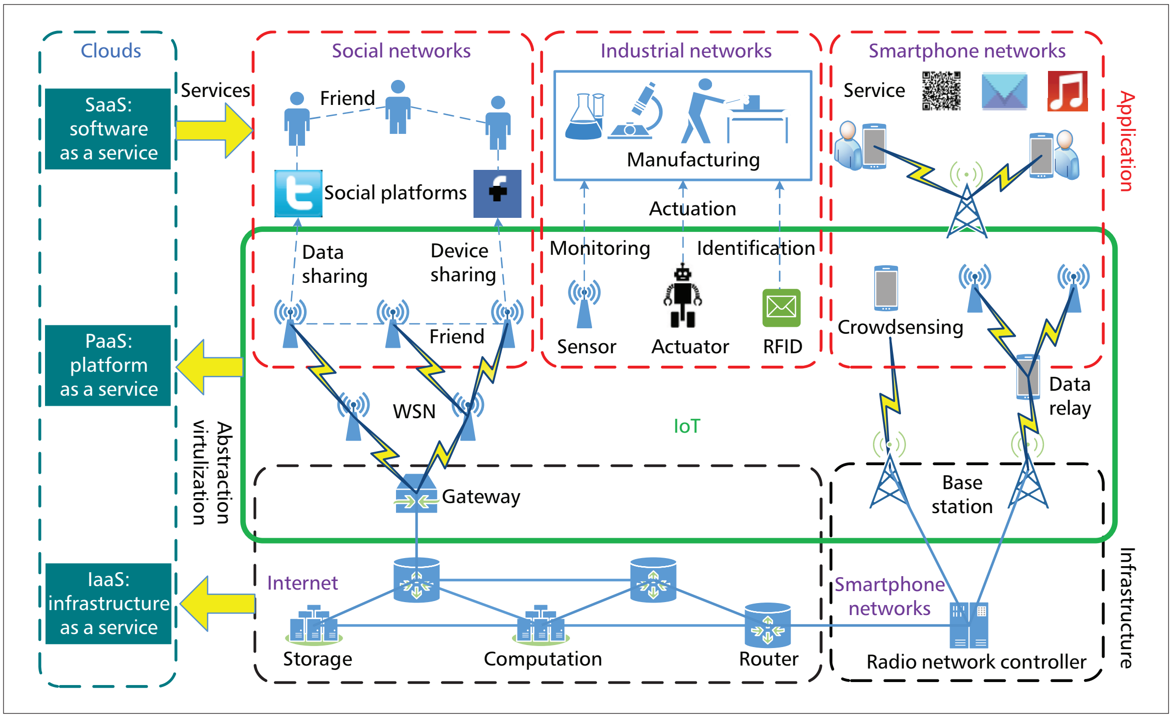

Figure 1. Interconnections between IoT and clouds, the Internet, smartphone, social, and industrial networks.

puting provides infinite computation and storage through a shared pool of resources, which can be dynamically allocated and easily obtained by any IoT application.

Cloud of Things

Although conceptual analyses are abundant in the literature, it is still questionable how IoT should be integrated with clouds. It is challenging to consider that objects are huge in number. They are largely dynamic, their life spans vary, and the provided applications require totally different quality of service.

A meaningful attempt can be found in [6], where a novel architecture, CoT, is proposed. CoT can be classified into four layers. The lowest layer, IntraNode, is responsible for management and abstraction of geographically distributed objects. Above it, the IntraCloud and InterCloud layers are designated to deal with object interactions inside an individual cloud and among heterogeneous cloud peers. The uppermost layer provides actual services to end users. Utilizing techniques such as volunteer contribution and mash-up,[1] CoT makes it possible for tiny objects to perform complicated, burdensome, collaborative tasks by delivering all decision making and computation-intensive work to clouds.

Big Data

The involvement of trillions of objects will raise the IoT data scale to an unprecedented level. The large size, high complexity, and wide variety of IoT raw data prevents traditional data processing techniques from discovering valuable information. Fortunately, big data is deemed a promising solution for IoT data management. Recent work [7] proposed a next-generation operational data historian (ODH) system, which is designed to store sampling data of objects for long periods, process real-time queries, and analyze historical data. ODH combines the advantages of a relational data model and a time series data model to support high write throughput and fast queries. All sampling data are packaged and compressed into regular time series (RTS), irregular time series (IRTS), and mixed grouping (MG) structures according to data characteristics. Compared to traditional databases, ODH improves data processing performance by one to two orders of magnitude.

Although progress has been achieved in this area, more research is necessary on issues such as data analyzing, knowledge creation, and event prediction.

ClouT

Recognizing the great benefits of IoT-cloud integration, lots of business organizations, academic institutions, and governments are investing significantly in related projects such as openIoT,[2] iGovernment,[3] Phenonet,[4] ClouT,[5] and European Smart Cities.[6]

Here, we take ClouT as an example. It is a collaborative project jointly funded by the European Community's Seventh Framework Programme (FP7) and the National Institute of Information and Communications Technology of Japan (NICT) in 2013. Leveraging cloud computing, city infrastructures will be provided with almost infinite processing and storage capacities, leading to a city with powerful elaborative faculty. On this basis, efficient communication platforms will be established to promote collaborations between objects and individuals. Through ClouT, data from objects will be precisely accessed, and universal human-object interoperability can be ensured. Following the concept of regarding infrastructure, platform, and software as services (IaaS, PaaS, and SaaS), objects will easily be shared among all citizens in the form of thing as a service (TaaS) and sensing as a service (SenaaS). We emphasize that not only does ClouT provide us with future visions, but a series of innovative applications and field trials

[1] Mash-up is a web application that uses content from more than one source to create a single new service displayed in a single graphical interface.

[2] http://openiot.eu/

[3] http://www.igovernment.in/

[4] http://www.plantphenomics.org.au/projects/phenonet

[5] http://clout-project.eu/home2/

[6] http://www.smart-cities.eu/

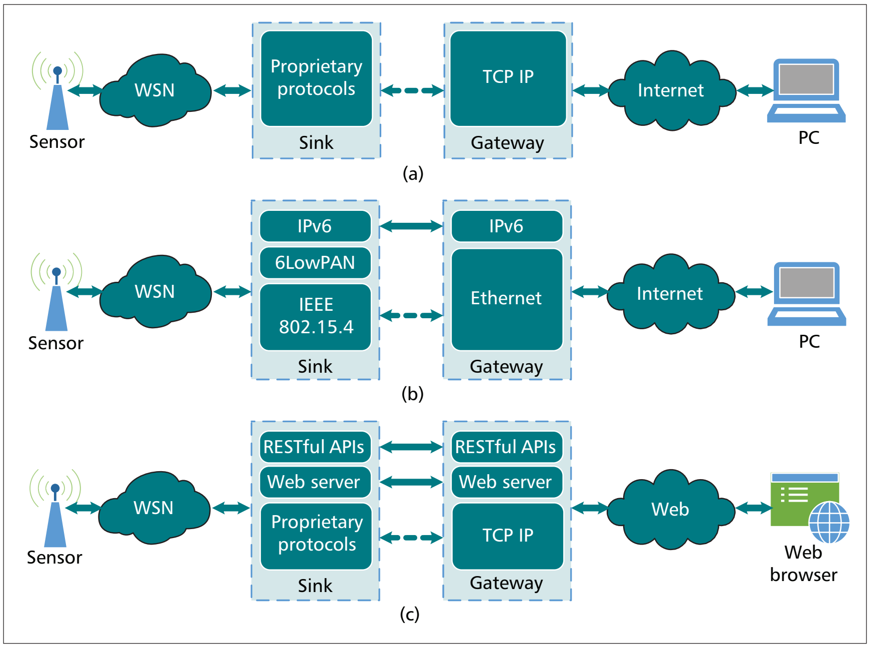

Figure 2. Integration of IoT and the Internet. Here, solid lines represent direct communication since protocols are the same, while dashed lines represent the opposite situation: a) protocol translation; b) IP over WSNs; c) WoT.

are also already in progress in cities such as Santander, Spain, and Mitaka, Japan.

The Internet

Due to the fact that the Internet is the largest network in the world, connecting IoT with Internet infrastructures seems to be an optimal way to provide the future universe with fast backbones.

Protocol Translation

In most scenarios, object resources are so limited that IP-compatible protocols are too burdensome to adopt, which hinders communication between objects and computers. To deal with it, protocol translation approaches are proposed, which interconnect sensors through proprietary wireless sensor network (WSN) protocols, while gateways act as proxies to convert proprietary protocols to TCP/IP and vice versa (Fig. 2a). With the assistance of dedicated translation gateways, proprietary protocols could continually focus on extremely lightweight protocols occupying minimal storage and obtaining maximal sensor lifetime without considering IP compatibility. Meanwhile, protocol translation provides a solution for legacy WSNs, allowing them to be connected to the Internet with little modification. This kind of approach is low-complexity, low-cost, and can easily be adopted. However, for lack of unified standards, it also causes isolation among IoT applications.

用网关将WSN专有协议转化为IP协议

IP over WSNs

Another group of researchers are making efforts to apply IP over WSNs. Compared to protocol translation, IP has several advantages. First, IP, as the de facto standard of the Internet, offers a flexible and extensible architecture. Second, a variety of IP-compatible mechanisms and protocols are already developed, validated, and operationally deployed in computer networks, which can easily be migrated to IP-enabled WSNs. Third, programmers, designers, and researchers are familiar with TCP/IP stacks. Thus, innovative ideas and techniques for the Internet could quickly be applied to WSNs.

Recognizing its benefits, the Internet Engineering Task Force (IETF) has selected IPv6 as the only choice to enable the wireless communication of WSNs and proposes an IPv6-based protocol stack, which consists of IEEE 802.15.4 as the physical and MAC layers, 6LowPAN as the adaption layer between IPv6 and IEEE 802.15.4 (Fig. 2b), IPv6 as the network layer, lightweight TCP/UDP as the transportation layer, and Constrained Application Protocol (CoAP) as a simplified application layer. However, as things are of different sorts and sizes, further efforts are still required to ensure that the proposed stack is adaptable to devices with different and limited capabilities. We refer the reader to [8] for a detailed discussion of recent standard activities.

Web of Things

Protocol translation and IP-based approaches focus on providing interconnected network infrastructures; however, they cannot solve the problem of various objects speaking various languages. For example, in a smart home, air conditioner, refrigerator, and stove temperatures are coded differently since they are produced by different manufacturers. A common language that can be understood by every object is urgently required.

Leveraging existing ubiquitous web protocols, WoT is totally application-oriented and aims at ubiquitous interoperability by giving every object web abilities. In a typical scenario, a gateway runs a web server and offers object functionalities via a RESTful[7] application programming interface (API) (Fig. 2c). Object information is obtained through a web browser installed on user devices. In WoT, all services are presented in the form of web applications. As long as web applications operate smoothly, network protocols can be tailored to a minimal degree. For example, Smew [9] is a prototype of WoT, which can be installed on most sensors because it only requires 0.2 kB RAM and 7 kB flash memory.

Smartphone Networks

The proliferation of smartphones has brought an explosive growth in smartphone networks. However, smartphones only cover areas with human activities. This disadvantage could be made up by IoT, because objects are always deployed in places that humans are unable to reach. Moreover, smartphone networks focus on communications among humans, while IoT mainly involves machine-to-machine (M2M) interactions. Integrating IoT with smartphone networks will produce a pervasive connected world with promoted human-object interactions, and full coverage of both dense human areas and remote areas. Based on three different roles, the smartphone performs as shown in Fig. 3. We divide this section into three parts, with each part described separately in the following subsections.

Crowdsensing

Crowdsensing is the concept of a group of individuals with mobile devices collectively monitoring, sharing, and utilizing sensory information of their environment with common interests. Compared to traditional sensors, mobile devices carried

[7] Representational state transfer (REST) is a distributed system framework that uses web protocols and technologies, and involves client and server interactions built around the transfer of resources. Systems that conform to REST principles are referred to as RESTful.

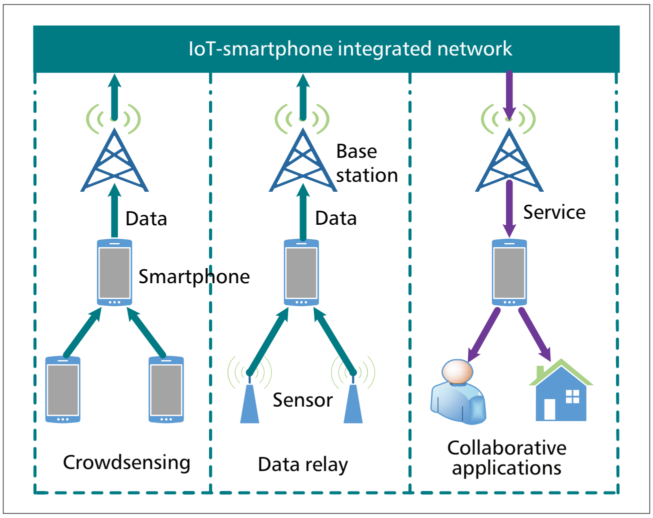

Figure 3. IoT-smartphone integration.

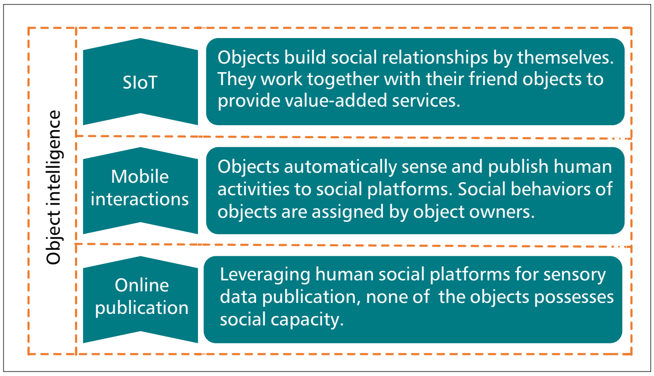

Figure 4. Stages of IoT-social integration.

by humans always incorporate powerful capacities, leading to more comprehensive sensory data and premium monitoring quality. The huge amount of mobile users and the pervasive distribution of humans significantly expand the potential monitoring area to a global scale. Human mobility, intelligence, and collaboration further promote the ability of crowdsensing applications.

Take CrowdSense@Place (CSP) as an example [10]. It is a framework for understanding different places that relies on opportunistically crowdsourced place hints, including words spoken by people, text written on signs, and buildings recognized in the environment. All places are classified into seven categories, including college, entertainment, restaurant, home, shop, workplace, and others. Employing crowdsensing and topic model techniques, CSP is able to recognize places with 69 percent overall accuracy. However, since crowdsensing participators vary frequently, the sensory information is exhibited in various forms (images, audio, video, etc.), and the data accuracy is different. Extracting appropriate environment parameters from a huge amount of information and assuring desired monitoring quality are the main challenges here.

Resilient Networks

Although network infrastructures are pervasively deployed all over the world, insufficient network access remains inevitable in extreme situations. For example, a large proportion of network applications (e.g., habitat monitoring, environment surveillance) are deployed in remote areas, where information infrastructures are inadequate and direct Internet access is often impossible. Another example is network outage caused by disasters such as earthquakes, floods, and hurricanes. A total of 385 telephone offices and 1.5 million users suffered from network breakdown in the great East Japan earthquake of March 11, 2011. Resilient networks are required to provide quickly constructed and low-cost network access in these situations.

Incorporated with communication interfaces, smartphones and sensors can be utilized to provide temporary network services when the network backbone breaks. Qu *et al.* [11] proposed that smartphones can serve as data relays for objects without Internet access. On the phone-object side, WiFi and Bluetooth are used to build low-cost communication channels for data collection whenever smartphones meet with objects. On the phone-Internet side, the collected data are uploaded to the Internet whenever phone owners move to areas with Internet access. Sakano *et al.* [12] proposed a novel network architecture that is resilient to disasters exploiting a specially designed movable and deployable resource unit (MDRU), which is a transportable container that accommodates modularized equipment for networking, information processing, and storage. Whenever a disaster happens, MDRUs are transported to the damaged area and mesh networks are constructed in a self-organized manner. Then network access and information communications can quickly be restored by interconnecting MDRU mesh networks to the network backbone. We refer readers to MDRU website[8] for more information.

Collaborative Applications

Objects are recognized as a main source of monitoring data and expected to stimulate innovative applications by intensive human-object collaborations. Installed with various apps, smartphones become a primary platform that first collects information from all kinds of sensors and then provides phone owners with favorable services leveraging the collected information. An interesting example is Lullaby [13], proposed by Kay *et al.*, which combines motion, light, temperature, audio, and photo sensors to provide a comprehensive record of an individual's sleep at night. The next morning, all of the collected records are transmitted to the smartphone. Through a smartphone screen, the user reviews graphs, analyzes factors related to her/his sleep quality, and finds potential causes of poor sleep. With the help of Lullaby applications, unconscious behaviors such as coughs, snores, and frequent motions are surprisingly identified, and users can make adjustments to ensure the best-quality sleep.

Social Networks

In the future, IoT services will no longer be provided by a single object but be presented in composite ways, which means many objects work together to accomplish complex tasks. Also, since most objects are possessed by individuals or organizations, people accessing the same group of sensors imply close social relationships. Together with the management requirements of a huge number of nodes, it is crucial to give objects social structures. In this way, network navigability can be guaranteed and objects can be accessed easily. Based on the degree of object intelligence, three identified stages of IoT-social integration are illustrated in Fig. 4 and described in the following subsections.

Online Publication

Nowadays, a large portion of IoT applications are designed for commercial purposes. Publishing information to interested users without delay is critical for business success. Compared to other data sharing mediums, leveraging social platforms possesses at least three advantages:

[8] http://mdru.org/

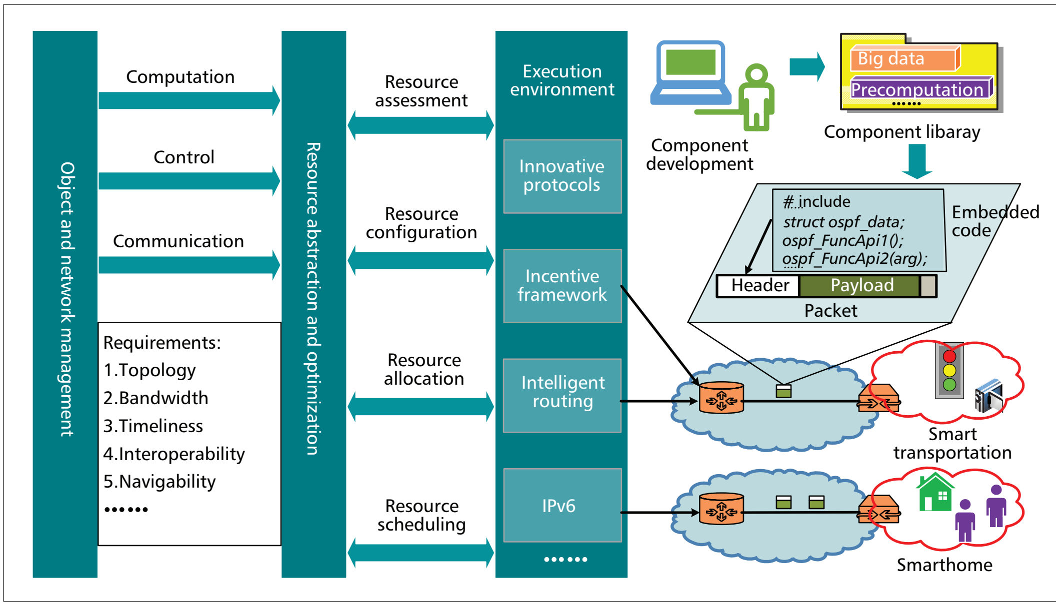

Figure 5. The future smart universe: a possible vision.

- They are prevailing platforms with extremely high user engagement and worldwide accessibility.
- Since human social relationships are clearly classified on social platforms, accurate data sharing and fine-tuned access control can be implemented easily.
- It provides a much simpler method of service discovery, advertising, and acquisition.

As an example, Baqer *et al*. [14] proposed S-sensor, a paradigm for sharing environmental information collected by sensors in the human-centric context of the Internet. Twitter is selected as the data sharing medium because it is a prevailing application with extremely high user engagement and worldwide accessibility, and it allows users to build communities according to social relationships or common interests; thus, information can be shared accurately. Tweets are consistent with the sensory data pattern, leveraging short messages to convey environment statuses. S-sensor includes sensor networks, base stations, and Twitter pages with functionalities that monitor the environment, connect sensor networks and the Internet, and exhibit shared information, respectively. Before publication, locally trivial raw sensory data are always processed (e.g., redundancy removal, exception filtering, secret hiding, data summarization) into meaningful short messages no more than 140 words that reflect the real important aspects of the environment. Connecting the physical world with human social networks provides new opportunities for environment understanding and application innovations.

Mobile Interaction

Propelled by the fast development of tiny wearable devices, more and more researchers realize that the human will become the center of information production and consumption. Therefore, the integration of IoT and social networks should not only provide convenience for data sharing but also promote human community awareness.

Following the idea of communicating by doing, Nazzi *et al.* [15] explored how to design objects with augmented functions that automatically generate and share activity information on social platforms whenever a human-object contact happens. To give a prototype application, an improved rollator (a tool to maintain balance for elders while walking) with wireless interfaces, actuators, and a dedicated screen has been designed, which is a smart device that can perform simple social behaviors. Without human intervention, rollators collect the walking status of owners and broadcast notifications to their friends. Upon receiving notifications, friends can predict the sojourn locations and join this journey. Applied in aged communities, smart rollators create additional openings for social interactions among senior citizens. However, social behaviors of these smart objects entirely depend on the social relationships of their owners.

Social Internet of Things

Believing that objects will obtain complete social abilities in the future, Atzori *et al*. proposed SIoT [16]. It envisions trillions of objects building their own social relationships autonomously rather than just participating in human social networks and serve as subsidiaries. Based on common interests, collaborations, and trustworthiness, objects can build friendships with other objects spontaneously to offer value-added services to humans. All relationships in the SIoT can be tuned to offer the network desired features such as navigability and scalability. However, to implement SIoT, great research efforts are required to solve challenges such as semantics to represent social relationships among sensors, mechanisms to autonomously discover heterogeneous objects and exchange profiles, and novel analysis algorithms to model relationships among trillions of objects.

Industrial Networks

In recent decades, the most notable trend in companies is probably the move toward networks at all aspects. The recent technological advances in automation, RFID, and sensor domains as well as the proposition of the IoT paradigm are transferring current industrial network systems to smart industries.

Industrial Wireless Sensor Networks

Nowadays, intelligent and low-cost industrial automation systems are urgently required to improve product quality and operation safety and reduce pollution. Installing tiny sensors in factories to monitor the critical parameters of circumstances, production processes, and key equipment could effectively promote factory automation. One example is IWSNs, presented by Krishnamurthy *et al.* [17]. They studied IWSNs through trial applications in semiconductor fabrication plants and oil tankers. Vibration sensors are used in both applications to detect impending equipment failures. Repairing or replacing defective equipment in advance not only guarantees smooth operations in factories, but also saves a lot of money. Meanwhile, IWSNs provide high-quality data with a relatively low investment in installation and operation, which validates the broad applicability.

INDUSTRIE 4.0

Many experts regard IWSNs as elementary forms of applying IoT in manufacturing. They believe that the further integration of IoT and enterprises will definitely lead to the fourth industrial revolution within 10 to 20 years. To ensure a global leading position in the manufacturing equipment sector during the fourth revolution, INDUSTRIE 4.0 [18] has been launched as a high-tech strategy with top priority by the German government, which aims to significantly promote the smartness of traditional industries. Specifically, INDUSTRIE 4.0 is a subset of IoT that mainly focuses on applying IoT concepts and technologies in manufacturing and business areas.

Taking full advantages of IoT paradigms, the INDUSTRIE 4.0 Working Group envisions future smart industries having the following main features: All stakeholders in the product value chains, such as raw material providers, factories, sellers, transporters, and customers, are seamlessly integrated. Hence, it is possible to meet multiple optimization targets including the lowest cost, fastest manufacturing, highest user satisfactions, and so on. Every product is uniquely identifiable by using RFID-tags and knows the details of its own manufacturing operations throughout its life cycle. Flexible working conditions are provided to workers to enable better balance between work and personal life, and employees focus on creative activities rather than burdensome routine tasks. Customers are involved in the design process of a single product, so specific requirements of each customer are satisfied.

A Possible Vision and Challenges

The integration of IoT and existing network systems is accelerating the formation of a unified smart universe. To achieve it, the spectrum of efforts required include not only academic innovations at a fundamental level, but also industrial collaborations on a wider range.

A Possible Vision

IoT has aroused great enthusiasm among researchers, engineers, and customers, and people hold different opinions on future cyberspace. To give an example, here we describe a vision with open, extensible, and flexible characteristics as a possibility for the future smart universe. As shown in Fig. 5, the leftmost layer is responsible for managing numerous objects and heterogeneous network infrastructures. During application deployment, user requirements including network topology, bandwidth, timeliness, and so on are collected. Then, based on techniques such as abstraction and optimization, all of these requirements are transferred into scripts and configured in network devices. Routers with reconfiguration ability [19] are highly demanded such that innovative protocols and incentive frameworks can be loaded, updated, and unloaded dynamically in the executable environments in the form of components. Rather than a small group of giant corporations, most components will be developed by individuals or tiny institutions, and component markets similar to the App Store will emerge. In terms of link transmission, executable codes are embedded in the packet header so that every packet knows how it will be processed over its entire lifetime. Although unable to be counted as a complete solution, innovative ideas and novel applications can be inspired by the proposed vision.

Challenges

From a long-term perspective, we identify the following challenges.

Resource Management: There are many factors that increase management difficulty for future IoT; for example, the huge number of involved objects, the complexity and variability of deployment environments, and constrained object capability. It is necessary to develop comprehensive resource analyzing mechanisms, quantitative resource assessment theories, and precise resource allocation and scheduling techniques.

Quality Assurance: The cyberspace is evolving to involve every aspect of the physical world, which leads to a mixture of applications that vary greatly in bandwidth, security, timeliness, and reliability requirements. Take factory surveillance as an example: to obtain a whole picture of a manufacturing process, both sensors and video monitors are deployed, where sensor networks require accurate data transmission with low bandwidth, while video streams require high bandwidth with low accuracy. Even simple application goals such as synchronizing sensory information and videos need extensive coordination of cable and wireless transmission technologies.

Extensive Involvements: Unlike most Internet devices that are possessed by a small number of giant Internet service providers (ISPs), in the future smart universe, most objects will be owned by tiny institutions and individuals. A user can be object designer, service provider, and customer at the same time. Relationships among stakeholders will become much more intricate, and services will be provided from heterogeneous environments; thus, robust and flexible information exchange techniques are required.

Trust: It is inevitable that hostilities and malice in human society will influence the interaction among objects in the future IoT. Trust mechanisms are required to help peers distinguish potential benevolent partners from hostile ones. However, this cannot be achieved easily considering the existence of identification theft, the uncertainty of object status, and conflicts between human communities.

Security and Privacy: Before IoT can be widely applied, security and privacy are major barriers that must be tackled. However, protecting IoT is an almost impossible mission due to the following reasons. A large part of IoT networks adopt lightweight wireless transmissions that are vulnerable to attacks [20], let alone the fact that objects are fragile devices themselves. Objects are distributed in various contexts to interact with heterogeneous devices, which complicates the design of protection mechanisms. Given that global connectivity and navigability are important features for IoT, attacks from local areas are prone to cause overall impacts. Novel techniques suitable for IoT applications need to be designed, including user anonymity, failure recovery, attack resilience, access control, and data encryption.

Incentive Frameworks: At the time most services are developed, shared, and purchased by individuals, service qualities will vary to a great extent due to the knowledge, professional, and skill variance of developers. Appropriate incentive frameworks are urgently required to encourage individuals to develop services with high quality, sharing premium services on a wide scale and protecting the security and privacy of service purchasers.

Conclusion

This tutorial provides a brief overview of the integration issue of IoT and some existing network systems. We have presented the latest achievements, representative technical solutions, and influential ongoing projects in both academia and industry. Some obscure interdisciplinary concepts such as CoT, WoT, SIoT, and IWSNs are explained. We believe that the proposed vision is a good start, although many open challenges still remain. However, based on the development trend of IoT combined with more insightful thinking, better solutions capable of providing better infrastructures and services for the future smart universe can be designed.

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