Toward Software Defined Smart Home

Ke Xu, Xiaoliang Wang, Wei Wei, Houbing Song, and Bo Mao

In recent years, the smart home field has caught wide attention and witnessed rapid development. Smart devices, continuously increasing in number, make user management and implementation more difficult while promoting the development of the smart home. How to design an efficient smart home management platform is one of the great challenges the current smart home field faces.

Abstract

In recent years, the smart home field has caught wide attention and witnessed rapid development. Smart devices, continuously increasing in number, make user management and implementation more difficult while promoting the development of the smart home. How to design an efficient smart home management platform is one of the great challenges the current smart home field faces. This article refers to the core idea of SDN, and proposed the software defined smart home platform, SDSH for short. The design features of virtualization, openness, and centralization can effectively integrate the heterogeneous network devices in the smart home platform, and flexibly adapt to the great difference between family scenes and user demands. At the same time, this article brings up the core technology of SDSH, and discusses the application value of the four core technologies and the new challenges the current technology is facing in a smart home scenario. In the end, regarding the SDSH application scenarios, this article analyzes the household experience innovation brought by this kind of smart home management platform, and the opportunities and challenges the SDSH platform faces.

Introduction

Along with the explosive growth of the Internet industry and the rapid increase in its economics, the demands for daily life intelligence are becoming higher. The prospect of the smart home is seen as a promising sunrise industry just like mobile Internet a few years ago, and has been in a stage of rapid development.

In the beginning of 2014, Google bought a company that focused on smart home devices, Nest LABS, founded by the father of the iPod (Tony Fedell) for $3.2 billion. When close attention was paid to Nest, the era of the smart home field came into being. In the same year, at the Consumer Electronics Show (CES), for the first time a number of smart home devices appeared on a large scale, such as the SleepNumber smart bed with its focus on health during sleeping, the Kolibree smart toothbrush, and the Belkin smart saucepan. In the exhibition, Cisco CEO John Chambers said that the Internet of Things (IoT) would bring $19 trillion worth of business opportunities, and in 2020, the world would have 50 billion items connected to the Internet. According to a survey data from QianJia.com, the growth of the Chinese smart home market is expected to be around 25 percent from 2012 to 2020, eventually reaching 357.6 billion yuan. The advent of the smart home era will greatly change the human way of life. Two years later, at CES 2016, the smart home still maintained strong growth momentum, and a lot of new products appeared and attracted people's attention, such as the Parrot flowerpot and Somabar robotic bartender (as shown in Fig. 1).

The academic field in recent years has been researching the cause of the large gap between the smart home vision and the real situation. Dixon and Colin's studies have found that on one hand, for ordinary consumers, it has become more and more difficult to manage their growing smart devices in the house [1]. On the other hand, the application software to manage these devices is hard to develop because of the extensive heterogeneity across homes, in aspects of devices, interconnectivity, and user preferences. This is problematic as users prefer to dynamically add a few devices or applications at a time [1].

In terms of the novel area of the smart home, industries and manufacturers have built many corresponding management platforms, such as Apple's HomeKit, Alibaba Smart Living, and QQ IoT. The HomeKit and its standard are regulated by Apple, and its application programming interfaces (APIs) are not open to the public. All input devices should be verified officially by Apple. After verification, smart devices can be available to customers through the iOS platform. Alibaba Smart Living takes advantage of its large online shopping platform. By selling smart devices, it provides the whole service from purchase to installation to use. Users can manually configure and operate between different devices on App. Different from Alibaba Smart Living, QQ IoT takes advantage of its strengthened communication app, and it emphasizes the feasibility of operation between devices and users, or between users. All the platforms mentioned above have been in use, and due to its strong commercial appeal, the smart home concept has attracted many smart device manufacturers and users. However, current smart home management platforms tend to simplify the increasingly complicated system into an app, leaving users to manage and operate. A self-management solution has not been found to deal with the problems of inconvenience men-

Ke Xu and Xiaoliang Wang are with Tsinghua University; Wei Wei is with Xian University of Technology; Houbing Song is with West Virginia University; Bo Mao is with Beijing University of Posts and Telecommunications.

tioned earlier such as increasing or adjusting devices, operating between devices, and using new devices. With the increase of smart devices and the complexity of application scenes, current so-called intelligent management strategies can hardly satisfy the needs of common users for the smart home.

Software Defined Network

The traditional network gained great success by adopting a hierarchical structure. But for the closed systems of network devices, we have to configure many devices with high complexity when business requirements change. At the same time, researchers also cannot deploy new protocols in the real environment. With the rapid growth of Internet traffic (it is expected that the global traffic will reach 1.6×10^{21} B [2]), users desire greater bandwidth and various new services. It is a big challenge, so we need a high-performance and high-stability network architecture that can be configured flexibly.

In 2008, Nick McKeown presented OpenFlow in [3]. And based on OpenFlow, they presented the concept of software defined networking (SDN) [4]. The basic structure of SDN is shown in Fig. 2, which contains the data plane and control plane. The data plane consists of the physical infrastructure layer and hardware abstraction layer. The control plane consists of network operating systems and network applications. These two planes are decoupled by a standardized communication protocol, which is always OpenFlow now.

SDN architecture has three main advantages. First, the open architecture of SDN realizes the centralized control and automatic management of networks. Managers can design, deploy, operate, and maintain networks on a centralized SDN controller rather than configure a large amount of heterogeneous devices. Second, the network operating system and network applications can be deployed on servers that adopt X86 architecture and can control data forwarding by OpenFlow. Thus, SDN can provide various open APIs to flexibly program networks. Third, SDN decouples the data plane and control plane by using OpenFlow, and virtualizes networks. A network becomes a logical resource that can be configured through software. For these advantages, the core idea of SDN has been used in the field of routers to build an open, flexible, and modularized reconfigurable router [5].

SDN, which solves many technological difficulties in traditional networks, is currently attracting significant attention from both academia and industry. It also receives wide research and application in data center and cloud computing areas; for example, [6] presents a novel cross stratum optimization (CSO) architecture in elastic data center optical interconnection. Reference [7] describes the architecture and implementation of Meridian, an SDN controller platform that supports a service-level model for application networking in clouds.

With the rapid development of IoT and the successful application of SDN in traditional networks, more and more attention has been focused on the research and application of SDN and IoT [8]. References [9, 10] use the idea of system design of SDN, proposing an IoT-oriented system structure design to deal with different challenges including network heterogeneity in traditional IoT systems, difference in service quality, and so on. Similar work has stimulated the combination of SDN and IoT technology. However, with the rapid development in the smart home area, due to its customer base, the requirements of system feasibility for easy operation and intelligence should be advanced. Meanwhile, the application scenes become more complicated because of different requirements, areas, times, and environments of users. The SDSH system we propose in this article has focused on the solutions to these two problems.

Figure 1. Smart home products.

Software Defined Smart Home

System Design and Platform Architecture

Applying the core idea of SDN (centralized, open, virtual) to the difficulties smart home faces, we now introduce the software defined smart home, or SDSH for short, shown in Fig. 3.

SDSH divides the smart home platform into three levels: smart hardware layer, controller layer, and external service layer. The smart hardware layer includes all kinds of smart hardware at home, such as smart sockets, SmartBand, sensors, and cameras. The controller layer is some kind of central management service; it can be physical hardware deployed at the user's home or abstract equipment deployed in the cloud, and can also be run from a traditional intelligent device. The controller layer is designed to shield the hardware details from the smart hardware layer, perceiving and analyzing user demands, and managing the smart home automatically and intelligently. At the same time, the controller layer encapsulates all kinds of summary information and docks the external service layer. The external service layer integrates the existing home service resources, supplying this emerging market with high-efficiency, high-quality, personalized services.

As shown in Fig. 3, the SDSH platform has different designs for smart hardware, controller, and external service layers. The smart hardware layer provides a general terminal subsystem for smart hardware at home, and uses virtualization technology to uniformly identify the computing, storage, and network resources of the whole smart home platform. Above this, through a unified system resource call and state report interface, the smart hardware layer converges system

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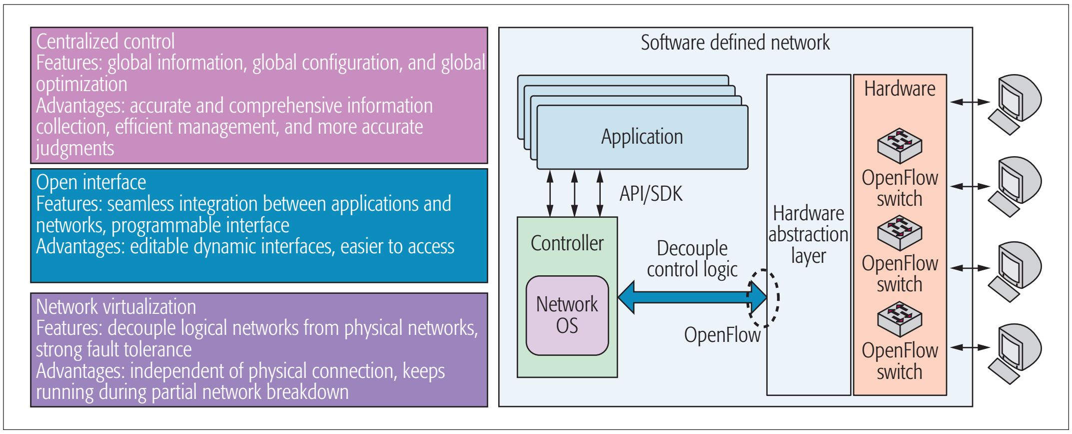

Figure 2. SDN architecture.

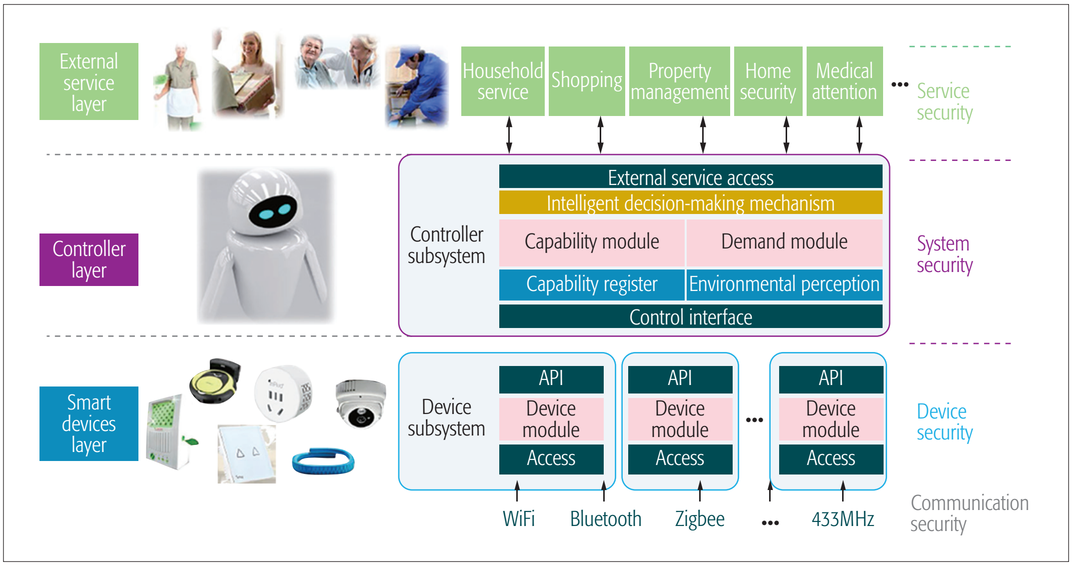

Figure 3. SDSH platform architecture.

resources and registers system capability to the controller layer.

The APIs for communication and interaction between the peripheral smart devices and central controller are on the top layer of the subsystem and the bottom layer of the controller. These APIs define the reported information from smart devices and the ability of the controller to manage the surrounding devices, mainly including the registration APIs when starting up smart devices or first connecting to the controller, status APIs, reporting ability APIs (function type, computing ability, network ability, storage ability, etc.), operation APIs, and so on.

Meanwhile, a smart device can selectively choose its APIs based on its own need, and through XML, it uploads and informs the controller of its script. In this way, different smart devices such as smart plugs, smart cameras, and smart TV sets can be customized with specific APIs based on their own requirements and methods of operation, thus enhancing the extensibility and feasibility of the system under different circumstances.

The controller layer in SDSH manages a large number of hardware in a smart home, and the controller subsystem deploys user demand perception technologies (natural language processing, indoor positioning technology, etc.), and a system resource and task scheduling artificial intelligence algorithm for shielding system complexity from users.

As shown in Fig. 3, controllers collect the resources and user requirements from the entire platform, and, forming a capability module and a demand module, manage the resources based on user requirements. Judging by system capability and overall requirements, controllers divide all the registered smart devices into several sections (system virtual machine) with standard functionality, network capability, storage capability, and so on. It also fulfills users' need for corresponding features. Through dynamic division, adjustment, and recycling of the sections, it achieves flexibility of overall resources in the platform. It also allows cooperation on many devices for multitasking based on multiple requirements.

The controller layer opens up authorization interface and system information, and offers unified access to an external service layer, which can form a unified, open, standardized smart home service market. Also, there are four levels of system security and privacy policy for communication: security, equipment security, system security, and business security.

Key Technologies and Challenges

In the SDSH platform, most of its key technology and challenges are shown in Fig. 4. First of all, there needs to be access and also a network technology that is compatible for all kinds of smart hardware devices. At the same time, virtualization technology should be used, which can shield the underlying communication details and abstract system resources and ability. Through automatic analysis and sensing of hardware data, acquiring the user demand non-inductively, the system capacity and user requirements are passed to the artificial intelligence decision algorithm, based on user history information and the current environment, to provide users with automatic, intelligent, and personalized home services. At present, the key technology of the four aspects, due to the change of the application scenario, will face a new challenge in the smart home field, which at the same time is also a new opportunity.

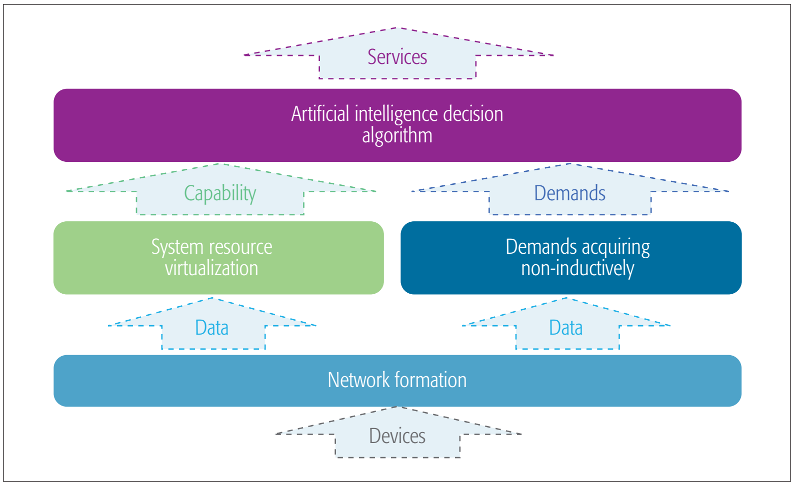

Figure 4. Key technologies of SDSH.

Demands Acquiring Non-Inductive Technology: How to perceive and understand the user's behavior is a foundation of the SDSH platform. Acquiring user demands is the beginning of all automation and intelligent management. In the traditional human-computer interaction, there are many ways to get user demands, such as command line input, peripherals like mouse and keyboard input, and touch input of mobile devices. However, considering the household environment, requiring users to input their demands all the time would be an unusual experience. How to acquire user demands non-inductively is the very first problem that should be studied for a smart home platform.

On this issue, two feasible schemes are natural language interaction and service based on the user's location (called location-based service, LBS). Among them, indoor positioning is the core of LBS technology, and the research on the current indoor localization technology has had a lot of achievements [11]. However, the current indoor positioning technology under this scenario has a lot of restrictions.

Due to the extensive use of Wi-Fi, localization technologies based on Wi-Fi received signal strength (RSS) fingerprints and smart devices (e.g., smartphones and tablet PCs) have received wide attention since 2000 [12]. As shown in Fig. 5, a Wi-Fi RSS fingerprint-based indoor localization algorithm can typically be divided into two phases: database construction and localization. In the construction phase, background RSS signal data in the target area will be detected and gathered, and a fingerprint database will be set up. In the localization phase, the Wi-Fi signal strength will be detected, and then the fingerprint database will be queried to determine the current position. However, because of the closer location binding relationship with users, wearable devices can be much more available for indoor LBS than traditional devices, but they also present a new set of challenges to indoor localization technology.

Energy efficiency is an essential issue that needs to be significantly improved for the existing localization technologies before they can be used in energy-constrained wearable devices. Current battery life in wearable devices is only a small percentage of that in traditional smart devices. Nowadays the indoor localization technology requires a certain amount of real-time RSS signals to ensure precision, which causes huge energy consumption for wearable devices; such devices may just work for a few minutes before the power wears out. And the much lower computing and storage capacity is also a big challenge for using the current indoor localization on wearable devices. The current technical solution for indoor localization still has great development potentials on using existing equipment to provide practical indoor LBS.

Network Formation of Smart Devices: SDSH requires each smart home device to communicate with the controller. A robust wireless ad hoc network is needed that can deal with node increase, node mobility, and node failure [13]. In the scenarios of the smart home, there are lots of mobile wireless devices and a large number of irregular obstacles. The only way to link these devices with the controller is to use a wireless ad hoc network.

But there are still lots of smart devices that do not possess the toos for network formation (e.g., Bluetooth). Now, as shown in Fig. 5, Bluetooth devices link with each other using a piconet, a star network with one master device that links with at most seven slave devices. With the number of smart devices increasing, the capacity of a piconet limits the number of smart devices that can be controlled by the controller. At the same time, smart devices can hardly communicate with a controller only by a single-hop network because of the short communication range and the numerous walls and obstacles. With the limited battery capacity, consumers are always struggling with the endurance of smart devices. From the above, it is important to propose a multihop Bluetooth network formation scheme with low energy consumption, network efficiency, and availability.

Bluetooth presents another network formation method named a scatternet [14]. A scatternet connects multiple piconets through bridge nodes that should work in both master and slave

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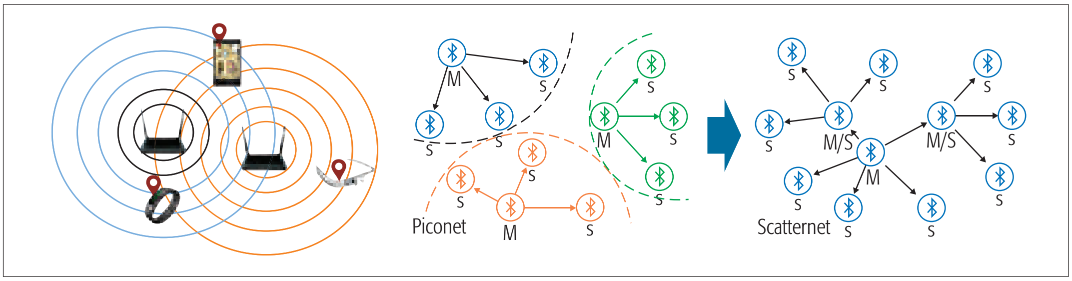

Figure 5. Indoor LBS and Bluetooth scatternet formation technology in SDSH.

modes, which is not supported by traditional Bluetooth chipsets. Faced with the growing demand of Bluetooth network formation, the Bluetooth Special Interest Group (SIG) proposed Bluetooth Core Specification v. 4.1 in December 2010. In this version, Bluetooth chipsets are allowed to work as a master and a slave at the same time in different piconets, which makes a scatternet possible.

System Recourse Virtualization: The resource virtualization method is introduced for abstraction, encapsulation, division, and combination of all kinds of system resources and system functions in SDSH. It shields the underlying system details and equipment features, and polymerizes or disperses the resourses of calculation storage and the network. This will meet different application scenarios and the network environment to form a good adaptable, scalable, and functionally flexible system support platform. And the more important thing is to relieve the user of the specific equipment operation and management, and give the user the real experience from the design of the smart home management platform. The virtualization method needs to study a mechanism for virtual distributed computing resources, storage resources, and large data storage, abstract function component abstraction and interaction mechanism design, network bandwidth and virtual address resources, and so on.

Virtualization technology has always been a research hotspot in the field of computer science, and cloud computing is widely used as a representative of virtualization technology. Virtualization products such as Tivoli Provisioning Manager (TPM) of IBM, Infrastructure of VMware, and SystemCenter of Microsoft have arisen at this historic moment.

In the smart home scenario, the use of virtualization technology will face some new challenges, such as heterogeneous networks, energy efficiency, personalized system composition, insufficient computing capacity, and design of privacy and security mechanisms. Traditional virtualization technology (e.g., cloud computing) emphasizes more on integrating system resources by way of optimizing scheduling to maximize the system processing capacity. In the smart home scenario, it shields the user from the features of underlying hardware to focus more on intelligent life experience and the smart home concept as a whole. To lower the difficulty of users and improve the smart home experience as the main targets, increased attention is given to ease of use and manageability, with less emphasis on the overall efficiency of the system scenario. How to design the corresponding virtualization technology also needs further research.

Artificial Intelligence Decision Algorithm: Currently, the controls of smart home devices are almost all based on scheduled rules, which have little flexibility and high complexity, and users cannot obtain a comfortable and convenient smart home service. With the continuous progress of deep learning and neural networks [15], artificial intelligence (AI) can constantly learn users' living habits without any artificial rules and then provide an automatic smart home service with continuous improvements. The real smart home will be reflected mainly in automation control and man-machine interaction by using AI technology.

An AI-based decision algorithm requires a data set as a training set to gain intelligent decision ability. SDSH can get data from various heterogeneous devices and provide a basic data set for smart home control. However, there is still no universal data model to formally describe the monitoring data of the smart home, so how to get a training set of the decision algorithm needs to be further studied.

An SDSH controller can control all smart devices, which not only gives AI decisions the powerful ability to provide users a holistic smart home service, but also places a greater demand on the accuracy of the decision algorithm. In the smart home scenario, misoperations (opening the door when there is no one in the house, turning on the electric kettle without water, etc.) may cause a great loss of lives and property. How to ensure a user's absolute safety and provide various control decisions as much as possible for user life also needs to be further studied in the field of AI.

Application Scenarios

Home Automation Services Based on the User's Location

Through the indoor localization system, SDSH can get the user's location information, and provide related functions and services. Smart devices have numerous manufacturers who provide products to perform tasks such as temperature sensing, intelligent air conditioning, intelligent light switching, and so on. The SDSH platform can integrate different manufacturers, device functions, and resources, making location-based services that fully exploit system resources and capabilities, and are convenient for user home life.

For example, judging by a user's entering or leaving a room, the platform controls the room

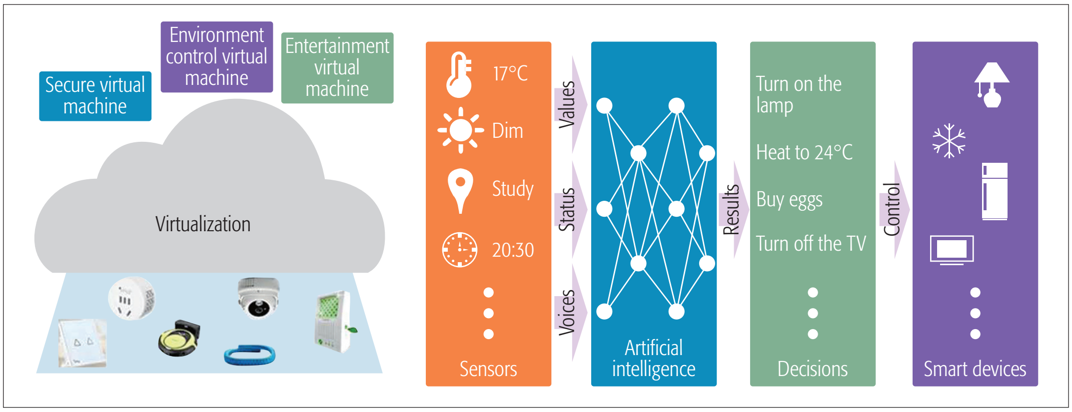

Figure 6. Virtualiztion and artificial intelligence technology in SDSH.

lighting equipment to turn on or off, or according to the indoor environment automatically adjusts the luminance of every light. When the user is in a room for a long period of time, the platform automatically opens room temperature control equipment through coordination with air conditioning and a temperature sensor for real-time control of the indoor environment.

Configurable Lifestyle Management

SDSH integrates user demands and system resources to provide standardized APIs and a decision making model. This open system enables potential service providers to push personalized, customized lifestyles to users' SDSH controllers based on age, gender, behavior, and family environment. For example, according to user's regular life schedule, service providers can push a healthy arrangement of meals to the user's controller, including when to eat and what to eat. SDSH can also get healthcare information from service providers, and set reasonable exercise times and sleep cycles for users.

At the same time, through further analysis of home environment parameters, or user preference behavior data, SDSH can provide real-time assessment of health status. When there is an health emergency, SDSH will generate a health check table based on user behavior and physical data and send it to private doctors through the cloud to implement intelligent assessment of the situation.

Condition Monitoring and Automatic Home Services

SDSH integrates home environment sensors, functioning as a real-time monitor detecting the status of the water supply and drainage, electricity supply, gas supply, and so on. This will provide an early warning against risk, and access the cloud services platform through the controller to release property maintenance requirements and reserve service visits. At the same time, through binding with an online payment platform, SDSH can automatically pay water, electricity, and gas fees.

The characteristics of rich open interfaces and programmable system design of SDSH make it possible that a large number of applications can be deployed through software upgrade. And there is no need to consider the communication technology and physical control of the underlying devices, which can effectively promote customization for the development of smart home applications.

Challenges and Opportunities

The software defined smart home has bright prospects; however, it also faces some challenges.

Family Privacy Protection

Because SDSH controls all the smart home devices as a whole, users not only obtain convenient services, but also face challenges in the field of security. SDSH collects massive data from users' smart home monitoring devices and then obtains users' living habits information by data analysis. This information provides accurate user requirements for personalized and customized services; however, it is a big challenge to ensure that this information is not stolen maliciously. SDSH controls all home devices. If the platform is invaded, everything in the home would be controlled by the invaders, which would huge economic loss, so SDSH requires high system safety and security.

Third-Party Services and Commercial Model

SDSH integrates requires of home services, and develops online to offline (O2O) mode in the field of domestic service. By connecting with SDSH, an online domestic service platform can obtain lots of families' services requirements. On the other hand, the online domestic service platform contacts separate home service providers and repair people. This model gets through the passage between online information and offline service. Consumers can publish their requirements rapidly and automatically and choose the server they want, thus avoiding the overcharge caused by information asymmetry. Meanwhile, home service providers can obtain requirements from a lot of consumers online, which decouple the housekeeping enterprises from geographic locations, and eliminate the rent of a storefront. Consumers, servers, and the online domestic service platform will create a win-win situation.

Relationship with the Existing Smart Home Platform

Aiming at the problems the smart home is facing, SDSH proposed a system design based on the core idea of software definition. SDSH has reference value for currently existing platforms such as HomeKit, Brillo, and the IoT platform of Tencent. Openness is an important part of the SDSH platform design concept. Through an open inter-

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The SDSH platform can provide specific services for all external services or other platforms with specific requirements, such as indoor localization, artificial intelligence decision algorithms, etc. This kind of service can rapidly improve the user experience or the system flexibility of other platforms.

face to implement the interconnection with other platforms, the use of virtualization technology is very helpful for reducing the heterogeneity and complexity of the platform caused by connecting different systems or different protocols. At the same time, the four key technologies proposed in this article give advice on the most important problem in a smart home management platform on different levels. The SDSH platform can provide specific services for all external services or other platforms with specific requirements, including indoor localization, artificial intelligence decision algorithms, and so on. This kind of service can rapidly improve the user experience or the system flexibility of other platforms.

Conclusion

Currently, the smart home should deal with problems of hardware differences, users' requirement differences, and underused monitoring data. For a breakthrough in the smart home, we propose the software defined smart home in this article by using SDN's strategies of centralization, optimization, and virtualization for reference. SDSH is centered on a controller that is compatible with various smart devices, and also provides open APIs to connect with third-party services. SDSH is related to the key technologies of demands acquiring non-inductive technology, network formation for smart devices, system resourse virtualization, and a decision algorithm based on artificial intelligence. SDSH discovers potential requirements of customers and provides a general smart platform to control devices. On this basis, SDSH can connect with external domestic services and form a generalized, standardized, and open smart home services market. SDSH is an open architecture with technological and commercial innovation, possessing great potential and bright prospects.

Acknowledgments

This work was supported by the National Natural Foundation of China (Grant No. 61472212), National Science and Technology Major Project of China (Grant No. 2015ZX03003004), the National High Technology Research and Development Program of China (863 Program) (Grant No. 2013AA013302 and Grant No. 2015AA015601), and EU Marie Curie Actions CROWN (Grant No. FP7-PEOPLE-2013-IRSES-610524).

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Biographies

Ke Xu [M'02, SM'09] received his Ph.D. from the Department of Computer Science and Technology at Tsinghua University, Beijing, China, where he serves as a full professor. He has published more than 100 technical papers and holds 20 patents in the research areas of next generation Internet, P2P systems, Internet of Things, and network virtualization and optimization.

Xiaoliang Wang received his M.Eng. degree in software engineering from Peking University in 2012. Currently he is a Ph.D. student in the Department of Computer Science and Technology at Tsinghua University. His research interests include wireless networks and wireless sensor networks.

Wei Wei (weiwei@xaut.edu.cn) received his Ph.D. and M.S. degrees from Xian Jiaotong University in 2011 and 2005, respectively. Currently he is an assistant professor at Xi'an Unviersity of Technology. His research interests include wireless networks and wireless sensor networks application, mobile computing, distributed computing, and pervasive computing.

Houbing Song [M'12, SM'14] received his Ph.D. degree in electrical engineering from the University of Virginia, Charlottesville, in 2012. Currently, he is an assistant professor with the Department of Electrical and Computer Engineering, West Virginia University, Montgomery, where he is the founding director of the Security and Optimization for Networked Globe Laboratory (SONG Lab, www.SONGLab.us).

Bo Mao is a graduate student in the Institute of Network Technology at Beijing University of Posts and Telecommunications. His research interests include wireless networks and wireless sensor networks application.