An Integrated Cloud-Based Smart Home Management System with Community Hierarchy

Ying-Tsung Lee, Wei-Hsuan Hsiao, Chin-Meng Huang and Seng-Cho T. Chou

**Abstract — ***This paper presents a smart home management system in which a community broker role is used for integrating community services, thereby reducing the workload of community management staff, providing electronic information services, and deepening the community's integration with the surrounding environment. At the home end, a home intranet was created by integrating a fixed touch panel with a home controller system and various sensors and devices to deliver, for example, energy, scenario information, and security functions. The community end comprises a community server and community personal computers, and connects to devices (e.g., video cameras and building automation devices) in other community systems and to the home networks. Furthermore, to achieve multiple in-home displays, standard interface devices can be employed to separate the logic and user interfaces. This study also determined that the message queuing telemetry transport protocol can provide optimal home control services in smart home systems, whereas hypertext transfer protocol is optimal for delivering location-based information integration services*[1].

Index Terms — Smart Home Management System, Community Broker, Cloud Services, MQTT

I. INTRODUCTION

Smart home technologies have developed rapidly from home networks and multimedia to various home automation systems. Particularly, these technologies are used extensively in home energy management, although their applications are mainly limited to individual households [1]–[3]. Because of the Internet of things (IoT), smart home technologies have begun to integrate various smart devices, ranging from conventional sensors and remote controllers to smart home appliances and robot systems. Consequently, many innovative applications have been developed. Recently, smart home technologies have been integrated with cloud-based services to provide value-added services, operations, and management.

Home energy management system (HEMS)-related devices are installed inside and outside residences (i.e., spaces accessible to the public); for example, solar panels are installed on residential rooftops. Consequently, building management concerns may arise [4]-[6]. Previous studies have suggested that hierarchical architectures composed of community units can promote data and service sharing among several families. However, these studies have lacked real environments in which to develop such architectures, often deploying the architecture on cloud platforms [7]. For example, most residential buildings in Taipei, Taiwan, are condominiums. In a condominium, the residential community is responsible for maintaining the environment, security guard services, and location-based services. The integrative function of community broker systems was an essential feature of this study.

This study proposed a community broker role for integrating community services, such as managing device operations involved in environment deployment, reducing the manual labor required of community management personnel, providing electronic information services, supporting diversified services, and extending the community's integration with the surrounding environment. In addition, integrating cloud-based services with community services can provide location-based services. Moreover, to achieve multiple in-home displays, standard interface devices can be employed to separate the logic and user interfaces (UIs). The aforementioned features were the major contributions of this study. On the basis of the implementation results, hypertext transfer protocol (HTTP) and message queuing telemetry transport (MQTT) protocol were compared. In summary, consistent with IoT characteristics, the MQTT protocol can be used to provide home control services in smart home systems, while HTTP can be used to deliver location-based information integration services.

The subsequent sections of this paper are organized as follows: Section II: Related Work; Section III: System Architecture; Section IV: Implementation Results & Discussion; and Section V: Conclusion.

[1] This work was supported in part by the Internet of Things Laboratory , Chunghwa Telecom Laboratories.

Y. -T. Lee is with the Department of Information Management, National Taiwan University, Taipei, Taiwan, R.O.C. (e-mail: d96725004@ntu.edu.tw).

W. -H. Hsiao is with Department of Computer Science & Information Engineering, National Taiwan University, Taipei, Taiwan, R.O.C. (e-mail: d03922031@ntu.edu.tw).

C. -M. Huang is with Internet of Things Laboratory, Chunghwa Telecom Laboratories, Taoyuan, Taiwan, R.O.C. (e-mail: chin_meng@cht.com.tw).

S. -C. T. Chou is with Department of Information Management, National Taiwan University, Taipei, Taiwan, R.O.C. (e-mail: chou@ntu.edu.tw).

Contributed Paper
Manuscript received 12/16/15
Current version published 03/30/16
Electronic version published 03/30/16

0098 3063/16/$20.00 © 2016 IEEE

II. Related Work

A literature review showed that studies on smart home systems have primarily emphasized three areas: smart devices, multiple displays, and cloud-based services.

A. Smart Devices

1) *HEMS-Related Studies, the Mainstream of Smart Home Studies*: HEMS studies have shifted from examining home energy management involving simple home-appliance measurements to investigating energy-generation mechanisms. Integrating cloud service platforms with environment-data acquisition has been gradually emphasized in HEMS studies [1]-[3].
2) *Solar Panels, a Popular Source for Generating Renewable Energy*: Solar panels are frequently installed in public spaces, thereby causing an overlap between HEMS spaces and community spaces. Although various energy-related systems can exist in a community, such as electric vehicle (EV) charging systems and central management systems related to monitoring public property, the space overlap arouses concern regarding integrating community operations and maintenance [4]-[6].
3) With advancements in the core technologies of energy conservation and renewable-energy generation, studies on smart homes have focused on examining people and events in smart home systems, such as hierarchical relationships and standby behaviors of controlled home appliances, user activities and satisfaction, and living environments. To accommodate increasing amounts of information, ultra-large cloud service platforms were developed not only to provide access to environment information, as mentioned previously, but also to store historical data of users' energy consumption. Therefore, such cloud service platforms are closely connected with smart house systems [7]-[9].
4) *Home Safety and Health Care:* In addition to energy management, home safety and health care have been explored in smart house studies. Smart home systems typically integrate various sensors and surveillance cameras to identify and assess abnormal events regarding home safety. In home health care, smart home systems not only employ body condition-specific sensors but also combine resources from remote cloud platforms with professional medical and healthcare services [10]-[12].
5) Many fields have applied smart home systems. In addition to the discussed fields, various fields have employed smart home systems for applying robot innovations and tagging techniques [13]-[15]: (1) When combined with cameras, robot systems can distinguish environments and provide feedback; therefore, exclusive, innovative robot designs are frequently applied to home automation. (2) Applying tags for object detection is the foundation of IoT technologies. Storing and analyzing the tag data on cloud platforms to ensure security and privacy has produced new applications.
6) Sensors and network technologies were used to develop the following innovative architecture applications [16]-[19]: (1) Home automation systems featuring hand-gesture recognition, (2) automatic photo-recommendation approaches based on detecting the activities in the photos, (3) emotion recognition and environment-interaction systems for videos, and (4) home-networking systems that enable long-distance visual sharing for families.

B. Multiple Displays

1) Smart home systems can choose display devices (e.g., tablet computers and smartphones) on the basis of the ambient environment and accordingly adjust the UI. A trend has developed in which smart home systems enable interactions between relevant devices as well as integrate surrounding sensors or remote servers. Moreover, TVs are a conventional home display interface. New studies regarding multiple displays have involved novel operational innovations, sensor integration, implementations of value-added services, and distinct screen systems [20]-[23].

C. Cloud-Based Services

1) *Cloud-Based Services Regarding Household Living*: To achieve high-level home automation, third-party servers and configured smart home systems are recommended to address data privacy and authentication concerns in inter-home, multiple-device smart environments. Smart home systems have been extended to intelligent building systems, with both indoor and outdoor scenarios being involved. In addition, regional environment information is used in the dynamic intermediate layers of the architecture. Integrating cloud-based services and smart home systems has generated the following challenges: (1) User terminals and servers must be hierarchically connected to develop data communication channels. (2) Software updating must consider regional software distribution. (3) Using cloud resources must entail security functions for accessing personal and group data. (4) To manage faults in the smart home systems, the cloud servers must cooperate with the core resource that manages the local servers to diagnose the faults through comparisons of events at different time points [24]-[28].

A summary of the discussed findings, in addition to research gaps and possible solutions, are shown in Table I. Moreover, Table I highlights the importance of the work discussed in subsequent sections.

III. Proposed System Architecture

A. Overall System Architecture (Three-Layer Hierarchical Architecture)

Typical smart home systems comprise single homes as well as various sensors and actuators. Smart home systems collect and present information through wired or wireless connections between the system and the home controller system. This study demonstrates a home-based smart home system, which connects single homes through community networking and integrates them into a hierarchical architecture on a cloud service platform over the Internet according to community categories. The community management system (i.e., community broker ecosystem) not only performs community and home management but also supports the functions of the surrounding facilities. Moreover, the cloud service platform performs consistent core management by integrating the smart home systems of the communities and homes. By integrating its global services, the platform provides overall value-added and extended services.

TABLE I
SUMMARY OF RELATED STUDIES AND RESEARCH GAPS

Category	Main Findings	Solution Gaps
Smart Devices (with Standard Interface and System Integration)	Smart devices must enable communications between distinct sensors with different interfaces.	A. The designs of existing architectures lack a standard interface control module (e.g., home controller) that possesses predefined and expandable communication interfaces.
	Smart devices must provide sensor functions and integrate smart home systems into community operations and management.	B. The designs of existing architectures lack a system-integrated component (e.g., community broker) that integrates community operations and management with local environments according to environment information.
Multiple Displays (about Standard Interface)	Multiple displays must select display devices and adjust user interfaces according to ambient environments, thereby transforming high-tech smart home systems into a simple and easy-to-operate home	C. The designs of existing architectures have no uniform user interface (e.g., home controller) capable of fulfilling the requirements of multiple displays.
Cloud Services: (for Service Intelligent)	Cloud services must be applicable in hierarchical architectures and combined with configured smart home systems to provide regional, location-based services (e.g., information services and home operation and management)	D. The designs of existing architectures lack an intelligent community configuration module (e.g., communication server and broker) to achieve location-based, multiregional applications of smart home systems and extend community operations and management.

In the subsequent sections, Fig. 1 elaborates the construction of the aforementioned hierarchical architecture, and Figs. 2, 4, and 6 demonstrate the architecture layers.

B. Proposed System Architecture

Fig. 1 illustrates the construction of the aforementioned hierarchical architecture, which consists of a home controller system, community management system, and cloud server platform. The home controller system comprises network connections, digital input and output (DIO) lines, RS485 wiring systems, and USB cables, through which the home controller system can integrate physical and conversion sensors and be extended to enable security settings, energy reporting, and scenario control. The community management system not only provides community and home management services and third-party services that enable communication with the cloud service platform but also integrates a central monitor and control system, surveillance system, vehicle-charging system, and digital signage system. Therefore, the community management system forms a location-based, integrated eco broker system. The core management on the cloud service platform focuses on the management and maintenance of communities and homes and provides remote control and data analysis functions to fixed carriers (e.g., fixed panels and smart TVs) and mobile carriers (e.g., smartphones and tablet computers). In addition, to achieve the goal of smart services, third-party applications and value-added services are integrated into the cloud service platform, thereby enhancing the diversification and convenience of the smart services.

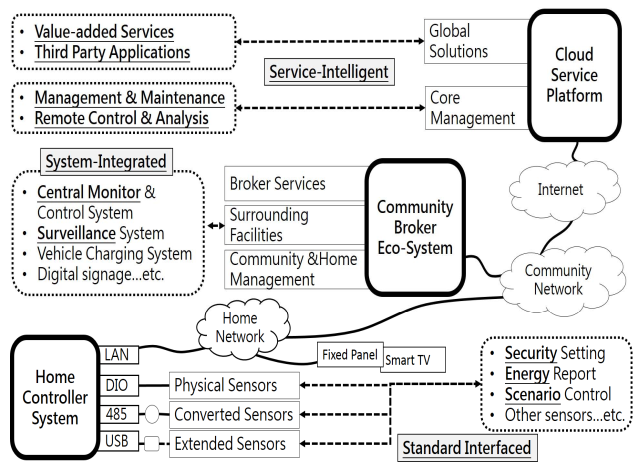

Fig. 1. Proposed system architecture.

C. Predefined Interfaces and Device Settings at Home

Fig. 2 shows the predefined interfaces and device settings at the home end. In this study, the predefined interfaces of the home controller system were designed to comprise a local area network (LAN), DIO lines, RS485 wiring systems, and USB cables. The LAN was used to connect the home network with the community network. The DIO lines were used to connect wired physical devices (e.g., emergency buttons, magnetic switches, and gas detectors and valves) and integrate power lines and motor devices through relay devices, thereby enabling the smart home system to conduct light control with on/off and dimmer options as well as curtain control with open/close options. Using RS485 wiring systems enables connecting RS485-related devices or an analog I/O converter with RS485-related devices, which include power meters, water meters, infrared (IR) controllers, and environmental sensors (e.g., temperature, humidity, and CO_2 sensors). Furthermore, in the smart home controller system, the USB slots can extend to wireless devices, such as devices compliant with the Zigbee protocol, including power plugs and PIR motion sensors. As shown in Fig. 2, various devices can be easily connected to the home controller system for fulfilling smart home functions (e.g., energy management, security, and scenario controls).

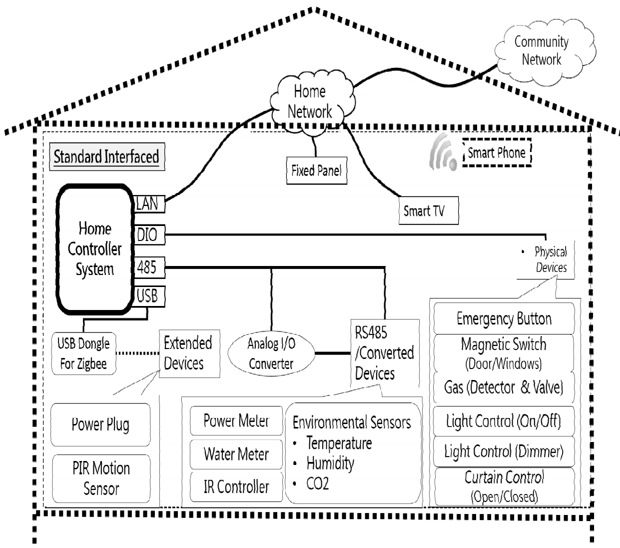

Fig. 2. Predefined interfaces & devices setting at home.

Solution gaps A and C (Table I) are addressed through the predefined interfaces and device settings of the home controller. After the devices are matched, the connection is configured, and the services registration and reporting processes are established, the system architecture proposed in this study can build data models of the integrated devices that connect to the home controller. Separating the configuration logic from the UI enables the various display devices to follow the arrangement for the menu and UI controls, thus creating similar UIs by selecting the managed devices and obtaining and setting the function values through the communication interfaces (Figs. 10 and 12). Such devices manipulations are not limited to proprietary apps issued for particular devices (e.g., an air quality detector and a heat exchanger from different manufacturers, Fig. 3).

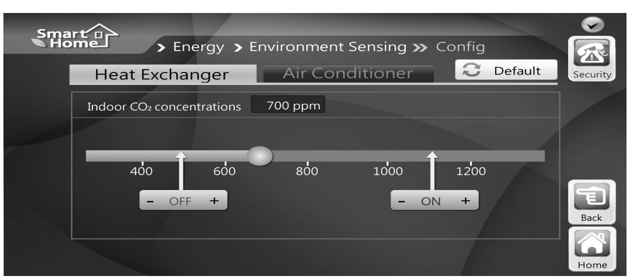

Fig. 3. Screenshot of heat exchanger triggered by air quality detector.

D. Functions and Integrated Systems in the Community System

The community management system is detailed in Fig. 4. The modules involved in the system include a broker service module (i.e., gateway for service and content), and a community and home management module. The community and home management module provides administrative tools for a security guard unit to manage residential affairs and affairs regarding condo status and alerts. Through the use of a graphic user interface, the community management system can perform emergency management and create a history log. Therefore, daily operations (e.g., notices regarding registered mail, parcels, and fees; announcements regarding water and power service interruptions and residential council meetings; and gas meter readings) become paperless, thereby enhancing operational efficiency and saving resources. In addition, to achieve integrated and comprehensive community services, the surrounding-facility-system integrated module focuses on integrating security systems (e.g., surveillance system, access control system) and building automation systems (e.g., central monitor and control system as well as a vehicle-charging system).

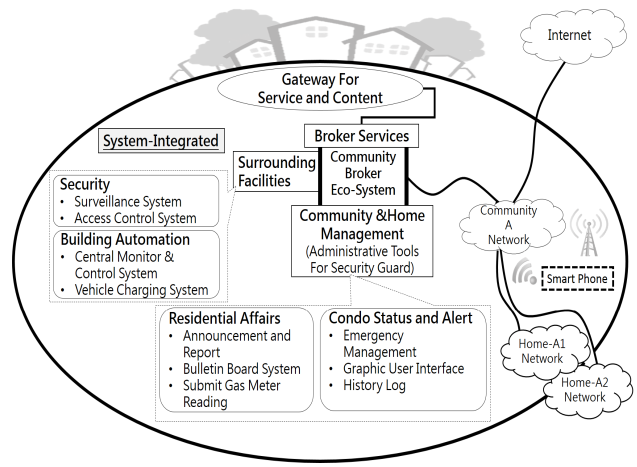

Fig. 4. Functions & integrated systems in community.

In summary, this study proposes a community broker that uses system integration (e.g., a schedule for door access control based on local time and weather) to provide value-added solutions such as a pop-up camera window on a local surveillance system triggered by detecting abnormal community-level door access (Fig. 5) or security alerts reported to a community guardian when residents press a home-level emergency button. Moreover, regarding long-term operations and maintenance, these integrated systems can proactively detect cross-system failures (e.g., a mail notice at the network level, a central monitor at the device level, and an alert log at the user level), thus reducing repair times and addressing solution gap B (Table I).

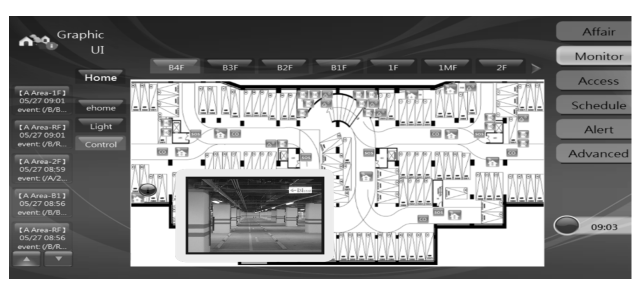

Fig. 5. Screenshot of local camera triggered by abnormal door access.

E. Platform Services and Modules on the Cloud

Fig. 6 presents a detailed illustration of the cloud service platform. The cloud service platform performs consistent core management by integrating the smart home systems of the communities and homes, in addition to providing overall value-added and extended services by integrating the global services of the platform. For conducting management and maintenance, the platform's core management module mainly comprises a community or home monitor and configuration and device information collection and analysis. In addition, the core management module employs a HTTP-based authentication and authorization system and an application login identity system based on the Smartphone for implementing remote-control operations. By applying the aforementioned functions of the core management module, the module enables multiple-display functions through fixed carriers (e.g., fixed panels, smart TVs) and mobile carriers (e.g., smartphones, tablet computers). Furthermore, to achieve smart service objectives, the global solution module on the cloud platform introduces third-party applications (e.g., healthcare, transportation, map, government information, and open-data applications) and various value-added services (e.g., music, photos, personal and family services, or news and weather forecasts).

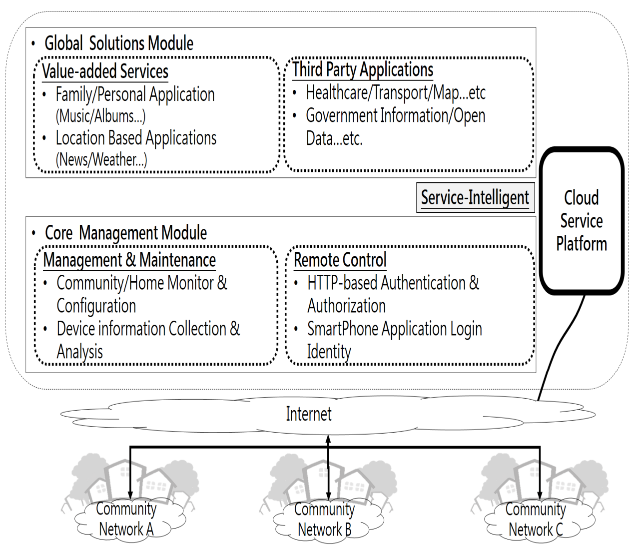

Fig. 6. Platform services & modules on cloud.

This study addresses solution gap D (Table I) by combining a community broker with a cloud server to provide location-based, multiregional applications. Hence, newscasts, weather forecasts, and government announcements could broadcast the nearest approximation information according to the geographic districts of the community configuration. Furthermore, a police officer (city government) could create a novel application by tracing the usage logs of residents in multiple regional communities (Fig.7) and scheduling location-based patrol services that optimize the allocation of police resources.

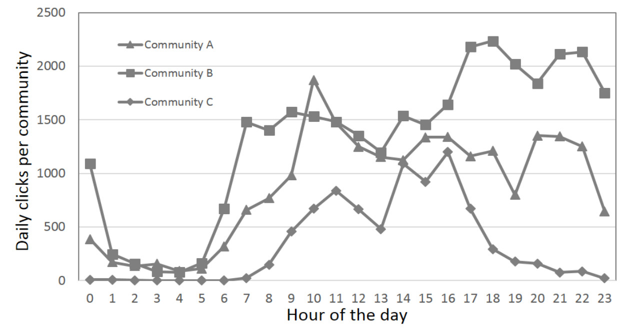

Fig. 7. Usage log examples in multiple regional communities.

IV. Implementation Results & Discussion

A summary of the configuration and device deployment in the various layers of the proposed hierarchical architecture is explained here. At the home end, a home intranet was formed by integrating a fixed touch panel with a home controller system as well as various sensors and devices to deliver energy, scenario, information, and security functions. The community end comprises a community server and community personal computers for security guards and connects to devices (e.g., video cameras and building automation devices) in other community systems through the community network and to the home networks through the Internet. The cloud platform that can be connected through the internet comprises a core management server farm and global solution server farm, and is used to connect third party servers. According to the proposed hierarchical architecture, consumers can access smart home services and multiple-display services over the Internet through various fixed and mobile carriers.

A. Home Controller Illustration

Fig. 8 illustrates the home controller in the home end. The primary home controller comprises not only a basic power supply and home networks but also five digital output devices, six digital input devices, and the RS-485 interfaces, as well as USB interfaces to ensure system extendibility. Table II displays the specifications of the home controller used in this study.

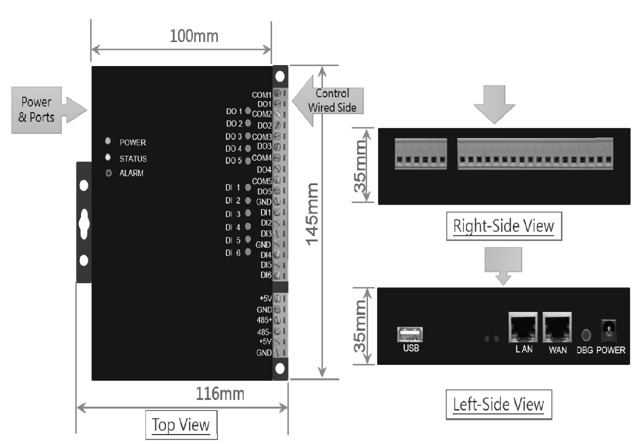

Fig. 8. Home controller.

TABLE II
HOME CONTROLLER SPECIFICATION

Components	#	Description
WAN	1	1 Port,10/100/1000Mbps
LAN	1	1 Port,10/100/1000Mbps
USB	1	USB 2.0、USB 1.1
RS-485	1	Half Duplex， 500Kbps，4 Pin (D+、D-、5V、Ground)
Console	1	Debug Console、 Jack: φ2.5mm Stereo Plug 、UART TX/RX
Digital Input	6	2.4≦High Level≦5V、Low Level≦0.8V
Digital Output	5	Relay Dry Contact *5、NC & NO Configuration by Jumper 1A/30VDC、0.5A/125VAC
LED Indicator	14	DI*6、DO*5、Power*1、Status*1、Alarm *1

B. Floor Plan Example

Fig. 9 shows the floor plan of a single home, detailing the layout of sensors and devices involved in the home controller. The home controller, network devices, power supplier, relays, and water and power meters are housed in an intelligent, integrated cabinet, which is placed beside a major partition wall to maintain the home's tidiness and overall appearance.

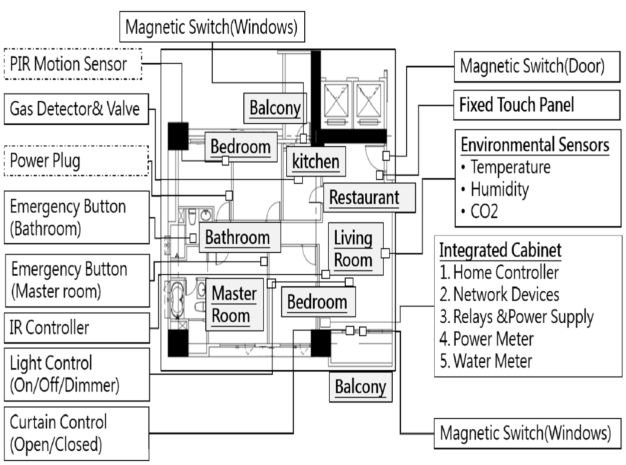

Fig. 9. Floor plan.

The primary fixed touch panel for the devices is installed at the door entrance, with magnetic switches being installed at the front door and windows of the balcony and rooms to ensure security. According to user needs, additional PIR motion sensors can be installed in the bedrooms to reinforce security. Emergency buttons are installed in the master bedroom and the bathroom for emergency purposes. When an emergency button is activated, community security guards may conduct a rescue operation. Moreover, to prevent accidents, gas detectors and valves are located in the kitchen, and environmental sensors (e.g., temperature, humidity, and CO_2 sensors) and an IR controller are installed in the living room. In addition, the air conditioner and TV can be consolidated for a state-of-the-art effect. Moreover, the light (on/off/dimmer) and curtain (open/close) control systems in the living room and bedrooms can be integrated with context-aware home automation. When additional services or devices are required, additional wireless power plugs can be installed to control the power supplies of other home appliances, thereby creating a convenient and comfortable smart home environment.

C. Screenshot of Implement Results

Fig. 10 presents screenshots that exhibit the various functions of the proposed fixed touch panel of the home controller. The Homepage mainly displays the function menu, calendar, time, weather information, and temperature. A security icon on the Homepage can enable placing an emergency call to the community security unit. The Energy & Scenario page provides information regarding historical statistics and real-time data collected from the water and power meters, enables single-touch control of the curtains and lights, and presents an integrative scenario control. The Security page presents statuses of the aforementioned magnetic switches and emergency buttons; this page can be used to enable a security mode when no resident is at home, which activates a real-time alarm upon detecting an intruder. Weather information is presented in the Weather page, which aids residents in deciding what clothes match the weather conditions and whether rain gears are necessary.

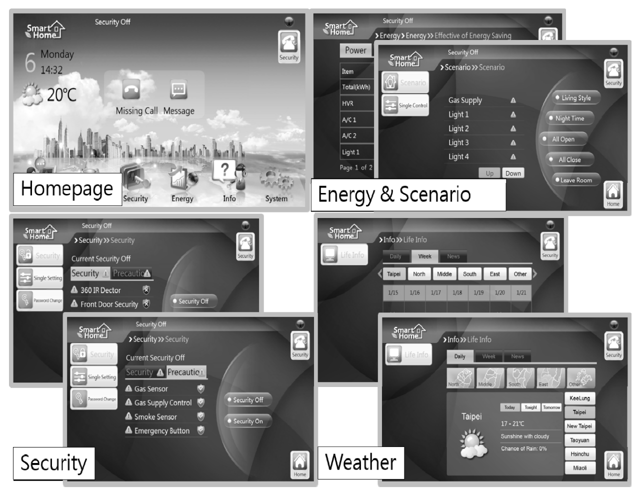

Fig. 10. Screenshot of functions at home.

Fig. 11. Screenshot of functions in community.

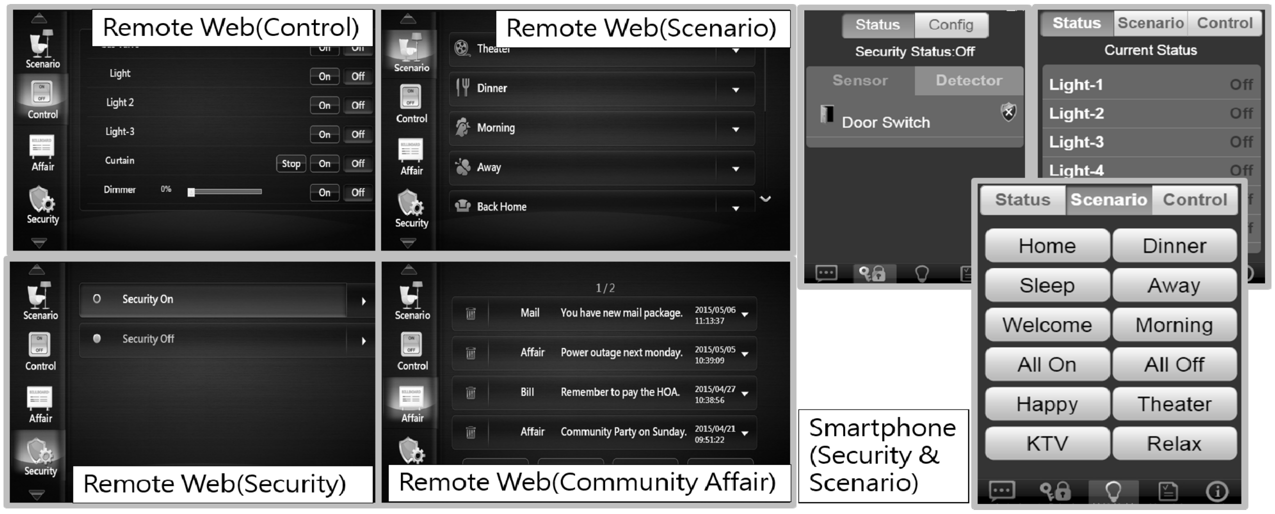

Fig. 12. Screenshot of multiple screen (remote web, smartphone).

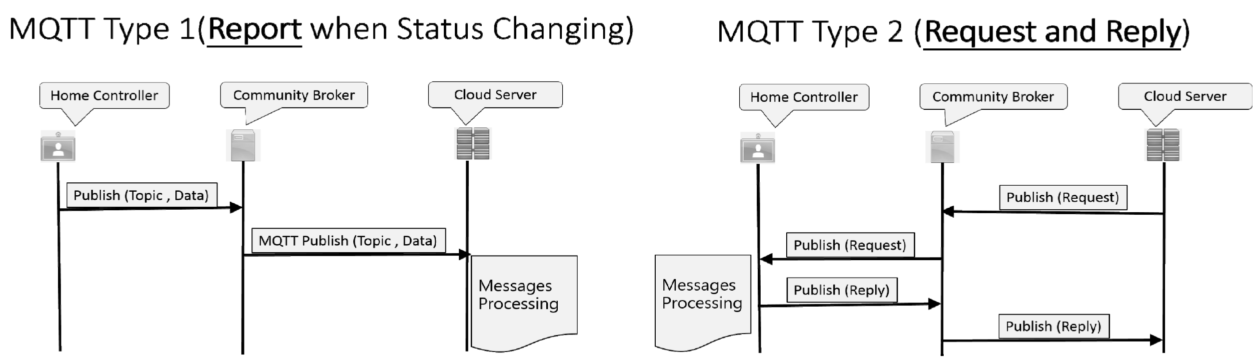

Fig. 13. Comparison of two abstract MQTT processes.

The function pages (Fig. 11) monitored by the server of the community management system present information regarding community affairs (e.g., mail notices, a gas meter report, and the community security guard and patrol schedule settings), the central monitor interface, the door access controls that manage overall community safety, and an alert log that records the alerts received and processed by residents.

Fig. 12 shows similar function displays on different display devices. The proposed smart home system allows users in offices to access home and community information through remote web pages. Moreover, employing the smart home system enables users to check home security and control scenarios on their smartphones when they are not at home. Therefore, the discussed scenarios exhibit the multiple-display feature of the proposed smart home system.

D. Service Protocol and Performance Evaluation

The proposed hierarchical architecture can use conventional HTTP and the IoT-influenced MQTT protocol. Previous studies have compared the power consumption, latency, and data traffic of the two protocols. For example, regarding maintaining connection operations, a connection established using the MQTT protocol consumed less energy than an HTTP connection did. Moreover, when the MQTT protocol and HTTP were applied to proxy servers separately, the MQTT-based proxy servers produced lower latency compared with that of the HTTP-based proxy servers. In addition, when tested in a global-positioning-system environment, the MQTT-based proxy servers resulted in lower data traffic than the HTTP-based proxy servers did.

To efficiently evaluate the feasibility of the proposed architecture for use in different scenarios, this study compared the data traffic and latency generated by the MQTT- and HTTP-based architectures. Overall, in contrast with the HTTP-based architecture, the MQTT-based architecture produced lower data traffic and lower latency in the command mode.

In addition, MQTT is characterized by the concept of topics and focuses on devices. Therefore, the number of community identifications (IDs) and home IDs in the architecture depends on the scale of services provided. However, the number of home devices can vary by time, which may incrementally affect the number of topics and the subsequent efficiency of the servers. Therefore, this study focused on one service scenario and proposed two types of abstract MQTT process to reduce the number of topics in the processes (Fig. 13).

The memory usages of the two MQTT processes were investigated. The virtual set size (VSZ) and resident set size (RSS) of each process were calculated, as shown in Table III.

- When the topic total and QoS level changed, the incremental amount of VSZ remained constant.

- When the topic total changed and the QoS level advanced, the RSS increased incrementally in a slow but steady manner.
- Overall, increasing to a large number of topics (e.g., 600) under a constant amount of connections required more memory than fewer topics (e.g., 4).

TABLE III.
MEMORY USAGE OF THE MQTT PROCESSES

Topics within 600 connections	QoS Level	Memory Usage Incremental Amount (kilo binary byte)		
		VSZ	RSS	Total
4	0	260	196	456
	2	260	202	462
600	0	258	336	594
	2	259	338	597

After the community broker load decreased because of the reduced topic total achieved through the aforementioned method, the core resources of the backbone networks and the cloud server had to be considered. As a core resource, the total connections employed in this study was substantially less than those in studies of conventional client-server architectures. The MQTT protocol only provides guidelines for connection security but does not stipulate imperative methods. Therefore, this study examined the bandwidth of the backbone networks and the processing capacity of the cloud platform by combining the MQTT protocol and the one time password (OTP) function of HTTP to enhance the safety of the proposed service architecture. The evaluation results of the consumption of the core resources indicated that, in contrast with conventional client-server architectures, the proposed hierarchical architecture integrated and saved energy by managing the bandwidth of the backbone networks and the processing capacity of the cloud platform.

This study had limitations and could be improved by implementing follow-up measures. For example, when the data traffic and latency generated by the MQTT- and HTTP-based architectures were compared, the difference in the MQTT and HTTP mechanisms resulted in the implemented architectures functioning differently. The comparison may not have been fair because different benchmarks were employed. In follow-up studies, a high level of consistency in the comparisons could be achieved by planning and comparing implementation scenarios (e.g., command-based scenario versus information-based scenario). Moreover, this study could be extended by including an examination of data analysis applications. For example, selecting service functions on the touchscreen of the community server to produce a record that can be analyzed to determine additional management scenarios involving the community features (e.g., personal preference of image modes and time-of-use information of the community guards), to adjust user-experience-based (UX-based) interfaces according to the relevance of user operation behaviors, and to detect obstacles by referring to the low click total and use rate of the services.

V. CONCLUSION

This study first proposed a hierarchical, smart home-service architecture, which employed standard interface devices at the home end to separate the logic and user interfaces, and achieving multiple in-home displays. Moreover, this study applied a community broker role to integrate smart home services such as managing environment deployment operations, reducing the manual labor required of community management personnel, providing electronic information services, supporting diverse services, and extending the community's integration with the surrounding environment. Therefore, a complete and integrated smart home system can be achieved. In addition, integrating cloud-based services with community services provided location-based services.

Subsequently, to investigate the effects of two application protocols (i.e., typical HTTP and the IoT-influenced MQTT protocol) on the proposed architecture, the data traffic and latency generated by the HTTP- and MQTT-based architectures were compared. In addition, further analysis of the MQTT protocol determined that the memory usage varied incrementally when the topic amount and QoS level changed. Furthermore, consistent with IoT characteristics, the MQTT protocol can be used to effectively implement smart controls in smart home systems, while HTTP can be applied to enable various location-based information integration services. Therefore, the OTP function of HTTP, which is typically used in commercial applications, was used to enhance the safety of the proposed service architecture. The consumption of core resources by relevant architecture components (i.e., backbone networks and the cloud platform) was evaluated and indicated that, in contrast with conventional client-server architectures, the proposed hierarchical architecture can save resources by managing the bandwidth of backbone networks and the processing capacity of the cloud platform.

This study recommends that follow-up studies employ data analysis applications and user perspectives in designing UX-based interfaces. This proposed hierarchical architecture is expected to transform high-tech smart home systems into simple and easy-to-operate home automation solutions.

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BIOGRAPHIES

Ying-Tsung Lee received the B.S. degree in Computer Science from National Chiao Tung University and the M.S. degree in Computer Science from National Chengchi University, Taiwan, in 1999 and 2001. He is pursuing Ph.D. degree at National Taiwan University, Taipei, Taiwan. His research interests include smart home, IoT, and cloud computing.

Wei-Hsuan Hsiao received the B.S. degree in Department of Information Management from National Sun Yat-sen University and the M.S. degree in Department of Information Management from National Chi Nan University, Taiwan, in 2002 and 2004.He is pursuing Ph.D. degree at National Taiwan University, Taipei, Taiwan. His research interests include smart home, IoT, and digital archives.

Chin-Meng Huang received the B.S. degree in Computer Science from National Kaohsiung First University and the M.S. degree in Communication and Networking from National Chung Cheng University, Taiwan, in 2000 and 2002. Since 2003, he has been with the Internet of Things Laboratory, Chunghwa Telecom Laboratories. His research interests include smart home, IoT and so on

Seng-Cho T. Chou received the Ph.D. degree in Computer Science from the University of Illinois at Urbana-Champaign. He is a professor in the Department of Information Management at National Taiwan University and served as associate dean of the College of Management, EMBA CEO and GMBA Convener at National Taiwan University. His research interests include Web technologies and services, e-business and e-commerce, knowledge management, data mining, and mobile and ubiquitous computing.