SERVICE-ORIENTED ARCHITECTURE FOR INTERNET-OF-THINGS BASED HOME AREA NETWORK

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DEDICATION

This thesis is dedicated to my family, supervisors, and friends, without whom, this work would be monumentally difficult. May Allah reward you all.

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ABSTRACT

The Internet-of-Thing (IoT) is rapidly expanding year by year in terms of device, network capacity, connectivity, and data traffic in existing and future 5G networks. Among the most prevailing applications of the 5G IoT network is in a smart home setting or a Home Area Network (HAN). However, the current IoT HAN faces several challenges such as inefficient utilization and management of sensor nodes, lack of interoperability in the heterogeneous sensor nodes, limited applications, and application development dependency. Therefore, there is a need to overcome such limitations to provide multiple applications running on HAN. The objective of this work is to develop a middleware based on a layered model and service-oriented architecture that ensures multiple applications running on efficient HAN. The proposed Service Oriented Home Area Network (SoHAN) middleware is made up of two sublayers called sensor dependent sublayer and service dependent sublayer. The sensor dependent sublayer comprises a task manager and aggregation manager that manage the various sensors' data and the service dependent sublayer consisting of scheduling manager, Quality of Service (QoS) manager, discovery manager, registry manager, composition manager and Data Distribution Service (DDS) manager handle multiple services that generate multiple applications. The SoHAN middleware was verified using simulation study and justified through implementation of a real testbed network. The simulation study shows that SoHAN generates the same packet rate as Smart Home and Ambient Assisted Living (SHAAL) and on the contrary 74.4% less compared to Ambient Intelligence Web Service Middleware (aWESoME). The result validates that SoHAN middleware uses adequate service packet size to carry multiple sensors' data that optimize the network throughput and efficiency. The network efficiency was further verified with SoHAN experiencing the least latency. SoHAN experiences 52% and 30% less delay compared to SHAAL and aWESoME respectively. The SoHAN energy consumption is reduced by 34.1% and 47.3% compared to SHAAL and aWESoME respectively. The least Central Processing Unit (CPU) usage means the SoHAN middleware incurs minimum energy usage. The performance of SoHAN middleware has been validated via experimental testbed. The result shows the SoHAN middleware enables low total disk usage and CPU usage by 21.4% and 9.5% respectively compared to without middleware implementation. In brief, the SoHAN middleware provides a significant achievement in terms of interoperability, scalability, reusability, and power efficiency in the IoT based HAN application.

ABSTRAK

Internet-of-Thing (IoT) berkembang pesat tahun demi tahun dari segi peranti, kapasiti rangkaian, kebersambungan dan trafik data dalam rangkaian 5G sedia ada dan akan datang. Antara aplikasi rangkaian 5G IoT yang paling lazim ialah dalam tetapan rumah pintar atau Rangkaian Kawasan Rumah (HAN). Walau bagaimanapun, IoT HAN semasa menghadapi beberapa cabaran seperti penggunaan dan pengurusan nod penderia yang tidak cekap, kekurangan saling kendali dalam nod penderia heterogen, aplikasi terhad dan pergantungan pembangunan aplikasi. Oleh itu, terdapat keperluan untuk mengatasi had tersebut untuk menyediakan berbilang aplikasi yang beroperasi pada HAN. Objektif kerja ini adalah untuk membangunkan perisian tengah berdasarkan model berlapis dan seni bina berorientasikan perkhidmatan yang memastikan berbilang aplikasi beroperasi pada HAN yang cekap. Perisian tengah rangkaian kawasan rumah berorientasikan perkhidmatan (SoHAN) yang dicadangkan terdiri daripada dua sublapisan yang dipanggil sublapisan bersandar penderia dan sublapisan bersandar perkhidmatan. Sublapisan bersandar penderia yang terdiri daripada pengurus tugas dan pengurus pengagregatan yang mengurus pelbagai data penderia dan sublapisan bersandar perkhidmatan yang terdiri daripada pengurus penjadualan, pengurus kualiti perkhidmatan (QoS), pengurus penemuan, pengurus pendaftaran, pengurus komposisi dan pengurus perkhidmatan taburan data (DDS) mengendalikan berbilang perkhidmatan yang menjana berbilang aplikasi. Perisian tengah SoHAN telah disahkan menggunakan kajian simulasi dan dibenarkan melalui pelaksanaan rangkaian tapak uji sebenar. Kajian simulasi menunjukkan bahawa SoHAN menjana kadar paket yang sama seperti kediaman berbantukan ambien rumah pintar (SHAAL) dan sebaliknya 74.4% kurang berbanding dengan perisian tengah perkhidmatan web kecerdasan ambien (aWESoME). Hasilnya mengesahkan bahawa perisian tengah SoHAN menggunakan saiz paket perkhidmatan yang mencukupi untuk membawa berbilang data penderia yang mengoptimumkan daya pemprosesan dan kecekapan rangkaian. Kecekapan rangkaian disahkan lagi dengan SoHAN mengalami kependaman paling sedikit. SoHAN mengalami 52% dan 30% kurang lengah berbanding SHAAL dan aWESoME masing-masing. Penggunaan tenaga dikurangkan sebanyak 34.1% dan 47.3% berbanding SHAAL dan aWESoME masing-masing. Penggunaan unit pemprosesan pusat (CPU) yang paling sedikit menunjukkan bahawa perisian tengah SoHAN menanggung penggunaan tenaga minimum. Prestasi perisian tengah SoHAN telah disahkan melalui tapak uji kaji. Hasilnya menunjukkan perisian tengah SoHAN dengan jumlah penggunaan cakera dan penggunaan CPU yang rendah masing-masing sebanyak 21.4% dan 9.5% berbanding tanpa pelaksanaan perisian tengah. Secara ringkasnya, perisian tengah SoHAN memberikan pencapaian yang ketara dari segi saling kendali, skalabiliti, guna semula dan kecekapan kuasa dalam aplikasi HAN berasaskan IoT.

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LIST OF ABBREVIATIONS

IoT	-	Internet of Things
SHAAL	-	Smart Home and Ambient Assisted Living
HAN	-	Home Area Network
M2M	-	Machine to Machine
WSN	-	Wireless Sensor Network
SOM	-	Service Oriented Middleware
SoHAN	-	Service Oriented Home Area Network
DDS	-	Data Distribution Service
MAC	-	Medium Access Control
CPU	-	Central Processing Unit
MA	-	Mobile Agent
OSGi	-	Open Services Gateway Initiative
aWESoME	-	Ambient Intelligence Web Service Middleware
HERA	-	Hardware-Embedded Reactive Agents
SYLPH	-	Services Layer Over Light Physical
KASO	-	Knowledge-Aware and Service-Oriented
OASIS	-	Open-source Architecture for Software Instrumentation of Systems
TinySOA	-	Tiny Service Oriented Architecture
QoS	-	Quality of Service
HD	-	High Definition
MIMO	-	Multiple Input Multiple Output
ITU	-	International Telecommunications Union
D2D	-	Device-to-Device
RFID	-	Radio-Frequency Identification
IP	-	Internet Protocol
WWW	-	World Wide Web
UWB	-	Ultra-Wide Band
METIS	-	Mobile and wireless communications Enablers for the Twenty-twenty Information Society

MN	-	Moving Network
DCPS	-	Data-Centric Publish-Subscribe
DLRL	-	Data Local Reconstruction Layer
SDN	-	Software Define Network
URN	-	Ultra-reliable network
UDN	-	Ultra-dense network
DB	-	Database
SMS	-	Short Messaging System
GPRS		General Packet Radio Service
WPAN	-	Wireless Personal Area Network
WLAN	-	Wireless Local Area Network
GUI	-	Graphical User Interface
ICN	-	Information-centric Networking
FTP	-	File Transfer Protocol
WSDL	-	Web Services Definition Language
XML	-	eXtensible Mark-up Language
MWSN	-	Multimedia Wireless Sensor Network
TA	-	Taint Analysis
TB	-	Trust Broker
VM	-	Virtual Machine
SOC	-	Service Oriented Computing
SCADA	-	Supervisory control and data acquisition
ADC	-	Analog-to-digital converter
FIFO	-	First-in-first-out
ITU	-	International Telecommunications Union
STNs	-	Smart Things Networks
FIA	-	Future Internet Architecture
FGF	-	Friendship and Community Forming
MuMHR	-	Multi-path, Multi-hop Hierarchical Routing
ASVM	-	Application-Specific Virtual Machine
DAViM	-	Dynamically Adaptable Virtual Machine
SQL	-	Structured Query Language
GSN	-	Global Sensor Network

DPWS	-	Device Profiles for Web Service
USART	-	Universal Synchronous/Asynchronous Receiver/Transmitter
MTU	-	Maximum Transmission Unit

LIST OF SYMBOLS

d	-	Sensor node
S	-	Sensor attach to the sensor node
V	-	Service
a	-	Application
$\bar{E}$	-	Energy consumption
E	-	Normalized energy consumption

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Research Background.

Internet of Things (IoT) is a network that interconnects objects from everyday life to create smarter homes, cities, transport, and health care systems[1]–[3]. The number of IoT devices is expected to range between 30 and 75 billion devices by 2025 [4]–[8]and hence they will represent the majority of the 5G network terminals. This large population of machines will use the 5G network to communicate with each other, with the human users, and send data collected by embedded sensors to the cloud for analysis and processing. Figure 1.1 presents the landscape of the 5G network.

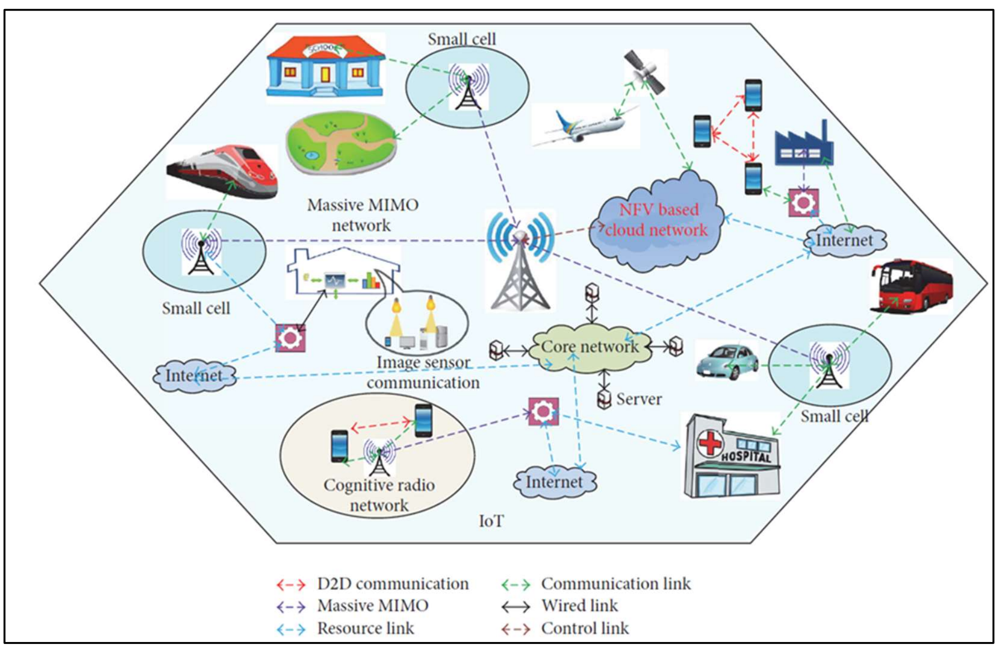

Figure 1.1 The Landscape of 5G Network[9]

IoT devices have acquired a significant share of the 5G systems design effort. Several components of the 5G network are designed to handle the IoT's scalability, heterogeneity, power, and cost requirements [10], [11]. Smart cities and health monitoring are among the most prevailing vertical applications of 5G networks [12]. Smart cities will involve highly dense clusters of wireless sensors that enable a large set of services and applications such as household electrical power consumption monitoring to enable power grid optimization, environmental services, access control, security system, and pollution monitoring. These applications demand highly efficient utilization and management of the sensor resources at the bottom level to secure stable operation and traffic intensity within the network that interconnects these nodes. These features are critical especially for applications such as health services, which are going to be revolutionized by 5G due to the capability of real-time health monitoring through wearables, in addition to enabling distant intervention by health specialists in cases of emergencies. Enabling a highly reliable operation for these critical services requires viable guarantees on system connectivity and latency, which might be hurdles due to network congestion and inefficient management of sensors.

Small cell technology is one of the key innovations in 5G, which provides greater coverage, less per bit cost and better networking performance. However, this transition needs large adoption, which is one explanation that 5G will only be introduced slowly in the next ten years or so rather than as quickly as possible. When ready, 5G can be fully compatible with all 4G and Wi-Fi networks. Smart homes are normally run using short range wireless networks such Wi-Fi, Bluetooth, and ZigBee. Contrary to 4G, 5G is used by a wider variety of wired goods with low-power applications. A wide variety of IoT gadgets are near our homes, including personal tablets, portable fitness sensors, intelligent lighting, digital locks, surveillance cameras and smart air conditioners. The latest wide-scale network offers a direct 5G link for any plugged-in computer, bypassing Wi-Fi for better efficiency. To continue to communicate more easily, all devices may link using the same protocol. The integrated IoT HAN promotes conveniences for homeowners. Smart home applications, including smart lighting, heating, protection, remote medical care, entertainment, are allowed by IoT HAN devices [13]–[15]. Homeowners may monitor them with a single device, typically a smartphone or a tablet, instead of multiple monitoring devices. As the smartphone and tablet are mobile devices, consumers can get reminders and alerts on home problems anywhere and at any time remotely. Smart doorbells, for example, enable homeowners to see and interact even though they are not at home. The indoor temperature, lighting and equipment may also be set and regulated by the users remotely via a mobile application. Although IoT HAN provides comfort and convenience, a few issues and challenges still exist. Among the problems for IoT HAN deployment in smart home applications are:

(a) Inefficient Utilization and Management of Sensor Nodes: The integration between application and hardware mandates that one or more sensor nodes are allocated for every smart home application. For example, room temperature control and fire alarm applications mainly sense the same quantity, temperature. This introduces redundancy in the sensors and the data they transmit due to the limited reusability of sensor nodes that adds to the cost and shortens node's battery life. Besides, the implementation of new smart home applications will essentially imply installing more sensor nodes. Hence, the transmission of all sensed data from these nodes will represent an overload on the network and increase its latency due to the increased probability of collision. Conversely, 5G network demands stringent latency specifications[16]

(b) Interoperability in Heterogeneous Networks: IoT smart home applications involve installing many sensing nodes from various manufacturers with essentially different wireless access technologies such as ZigBee, Bluetooth Low Energy (BLE), and Wi-Fi[17]. Two nodes employing different technologies cannot achieve direct machine-to-machine (M2M) communications and thus are incompatible[18], [19]. For example, in a home security application, a motion sensor that uses Bluetooth technology will not trigger a camera that uses Wi-Fi technology to capture an intruder's picture. A straightforward solution to this problem is to employ a gateway server to connect these nodes; however, this solution has drawbacks such as cost, the difficulty of usage, and maintenance[20].

(c) Application Development: The conventional approach for developing smart home applications is usually tailored for a specific sensor node type and requires the developer to be aware of low-level details of node operating system and programming, sensor operation, and its wireless access technology. It becomes even more challenging to develop an application that supports heterogeneous sensors that use different transmission technology and run on different operating systems[2], [21]. As a result, the overall application development time and cost are high.

1.2 Problem Statement.

The IoT for HAN applications normally consists of heterogeneous sensor nodes which are a collection of different types of physical sensors, microcontrollers, and wireless modules. The sensor data which is the signals measured by the physical sensor will be processed by the microcontroller before being transmitted to the gateway via the wireless module. The gateway will process the sensor data and send it to a specific application. Traditionally, a specific sensor data in HAN belongs to a specific application and at the same time, the sensor data can't be used by another application. This means the sensor service is tight coupled with the application service.

The inter-dependencies design of the sensor service and application service has a few drawbacks. When a new application is introduced that requires the existing sensor service, a new sensor service needs to be added to support that application. The application can use the existing sensor service in the HAN. However, this requires modification on the coding at the sensor node and gateway. Hence, there will be an increase in the deployment cost and not a practical solution whenever there is a need to add new applications.

To overcome the tightly coupled services between sensor node and application, SHAAL[22]introduces a service where all the sensor data offered by a single sensor node will be combined into a single service. This service will be encapsulated into a packet and transmitted from the sensor node to the application layer via a gateway.

This method requires a lot of power for processing and transmitting the packet because of the large packet size. In addition, the sensor node will send all the sensor data without considering which sensor data is required by the application. This will become impractical if the sensor node is attached to many physical sensors. The issue can be resolved if only the sensor data required by the application is transmitted to the gateway.

aWESoME[23] middleware offers a single service with a single sensor data. It means the service only contains a single sensor data encapsulated into a packet before being transmitted to the gateway to serve an application requirement. Not all the sensor data will be transmitted and only a specific sensor data required by the application will be transmitted to the gateway. However, this method will consume a lot of power during packet transmission if the application requires more sensor data from the sensor node. Since only one sensor data is allowed to be transmitted into the packet, it will cause network congestion that can lead to higher packet collision if more packets need to be transmitted into the network. Therefore, there is a need for the middleware to allow a service to contain more than one sensor data to mitigate network congestion and packet collision. Only the sensors' data required by the application will be attached to the service. One of these systems produces an insightful IoT home area network (HAN)[24]

1.3 Research Aim and Objectives.

The main goal of this work is to develop a service-oriented middleware that allows multiple applications running on a single sensor node in HAN. The middleware has been designed based on a layered model that can provide interoperability, scalability, good Quality of Service (QoS), reusability and scalability. The specific objectives are defined in the following:

(a) To propose a SoHAN framework that establishes interoperability between heterogeneous sensor nodes.

(b) To investigate SoHAN middleware performance through simulation.

(c) To evaluate the performance of SoHAN middleware in a real experimental testbed.

In this work, the performance of the service-oriented middleware is measured based on the packet generated, packet loss, latency, and energy consumption. The CPU usage, total disk usage and end-to-end performance of proposed service-oriented middleware is evaluated in the real experimental testbed.

1.4 Research Scope.

The work is divided into two parts which are the design of SoHAN middleware and the investigation of its performance in simulation and real experimentation. The proposed middleware supports multiple applications running on a single sensor node. The SoHAN middleware has been designed based on service-oriented architecture by using the layered model. The SoHAN middleware is divided into two sublayers which are sensor dependent sublayer and service dependent sublayer. Both layers are independent from each other.

The design of the sensor dependent sublayer consists of three functional managers, namely, the data acquisition manager, the task manager, and the aggregation manager. The sensor dependent layer offers the scalability and interoperability where a sensor can be easily added into the architecture as the control plane provides the process flow for easy integration with the system. The second sublayer is the service dependent sublayer where it consists of five functional managers, namely, the service composition manager, the QoS manager, the discovery manager, the registry manager, the scheduling manager, and the Data Distribution Service (DDS) manager. The service dependent sublayer offers scalability, reusability and QoS.

The SoHAN middleware will be simulated using MATLAB to study its performance in terms of packet size, latency and power consumption as compared to the existing middleware. The SoHAN middleware will be implemented onto a real experimental testbed consisting of one unit of Raspberry Pi 3, 2 units of wireless sensor node and a personal computer to study its end-to-end performance such as latency, CPU usage and total disk space usage in the HAN environment in comparison to without the middleware.

1.5 Thesis Outline.

The rest of this thesis is organized as follows.

Chapter 1 presents the introduction, the problem statement, the objectives, and scope of the research work.

Chapter 2 provides a comprehensive overview of the proposed research work. It presents the current innovations and service models for mobile systems and HAN. The IoT and architectures are described in this chapter. The background and concept of middleware architectures for Wireless Sensor Network (WSN) and IoT as well as a detailed taxonomy of middleware architectures for IoT are also presented. The chapter is concluded by summarizing related works and their limitations to identify the research gaps.

Chapter 3 introduces the overview of the SoHAN middleware. The proposed SoHAN middleware with sensor dependent sublayer and service dependent sublayer is illustrated. The application model for the proposed middleware that includes the sensors, services and applications is explained. The network model for proposed SoHAN middleware, the assumptions used, and its performance metrics are also presented.

Chapter 4 presents the design of SoHAN middleware. The detailed operation and implementation of SoHAN middleware which include the sensor dependent sublayer and the service dependent sublayer are described in this chapter. The functionalities of managers in both sublayers are discussed. The features of SoHAN middleware are also explained. Lastly, the summary of the chapter is presented.

The performance study and analysis of SoHAN middleware in simulation and real experimental testbed will be elaborated in Chapter 5. The simulation model, simulation setup, simulation results and analysis are explained. This is followed by a discussion on the experimental model, experimental setup, and results.

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