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An Ontology-driven ECHONET Lite Adaptation Layer for Smart Homes

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Abstract: ECHONET Lite is a leading protocol for controlling devices in Japan smart homes. However, it lacks interoperability with service platforms that provide ambient assisted living (AAL) services to residents which are actively researched in order to deal with the population aging. This research proposes an adaptation layer for ECHONET Lite protocol which provides the semantic interoperability based on ontology. In order to verify the proposed solution, a service gateway based on the proposed architecture was implemented to integrate ECHONET Lite protocol into the universAAL platform, a leading AAL platform in Europe.

Keywords: ECHONET Lite, smart home, ontology, ambient assisted living, system integration

1. Introduction

In accordance with the development of the IoT, ambient assisted living (AAL) [1], is a promising candidate to deal with the global issue of aging population [2]. AAL utilizes information and communication technologies (ICT) and smart home technologies to support independence and improve quality of life for elderly people [3]. There have been many efforts to propose as well as implement service platforms and middleware platforms to support AAL, however, interfacing heterogeneous devices from different vendors and network technologies is a challenging problem for making AAL platforms real [4]. Therefore, semantic level interoperability has become a requirement for the IoT as stated in ITUT-Y4111 [5] and it is the key aspect to integrate hardware devices to AAL service platforms thus enables AAL services for smart homes.

In Japan, it is expected that the number of smart homes reaches 7 million by 2024 [6] and ECHONET Lite protocol, an ISO/ICE standard, is designed as the country's recommended standard for HEMS equipment [7]. ECHONET Lite is a network protocol that provides a standard way to control household appliances to achieve interoperability between devices from different vendors locally. However, it lacks to support the interoperability with service platforms outside of the home network. Meanwhile, ontology provides the highest level of semantic clarity and ontology driven approach provides a lower cost solution when dealing with diverse data sources [8]. Ontology is one of the basic requirements to provide semantic description for the IoT resources [5] by sharing the common understanding of the structure of information between components.

This work addresses this need for semantic level interoperability of ECHONET Lite devices by proposing an ontology driven adaptation layer (AL). This AL consists of the following two components:

- An ontology model which is compatible with ECHONET specifications and is able to merge with other ontologies (different domains).
- An architecture to support managing and monitoring a network of ECHONET Lite devices and utilize the ontology model to support semantic annotation for data and services of the network of ECHONET Lite devices.

Furthermore, the intergration of ECHONET Lite protocol into the universAAL, a semantic supported AAL platform, was implemented to evaluate the proposed AL.

2. Background

2.1 The ECHONET Lite Protocol

ECHONET, which has become a de facto home network standard certified by ICE and ISO, stands for Energy Conservation and Homecare Network. However, the ECHONET protocol did not attain widespread adoption due to two major factors. Firstly, the specification requires a more complicated system configuration for multiple controllers and multiple devices. The other factor was the overall complexity of the protocol, leading to only a few compliant implementations. Therefore, in 2011 it was redesigned as the substantially simplified ECHONET Lite protocol.

ECHONET Lite has become a leading interface used in smart homes in Japan and the number of devices compatible with the ECHONET Lite protocol is growing steadily [9]. The basic concepts of the ECHONET Lite protocol are illustrated in **Fig. 1** where a network of ECHONET Lite devices is a collection of *Nodes*. A node is a physical device that connected to the net-

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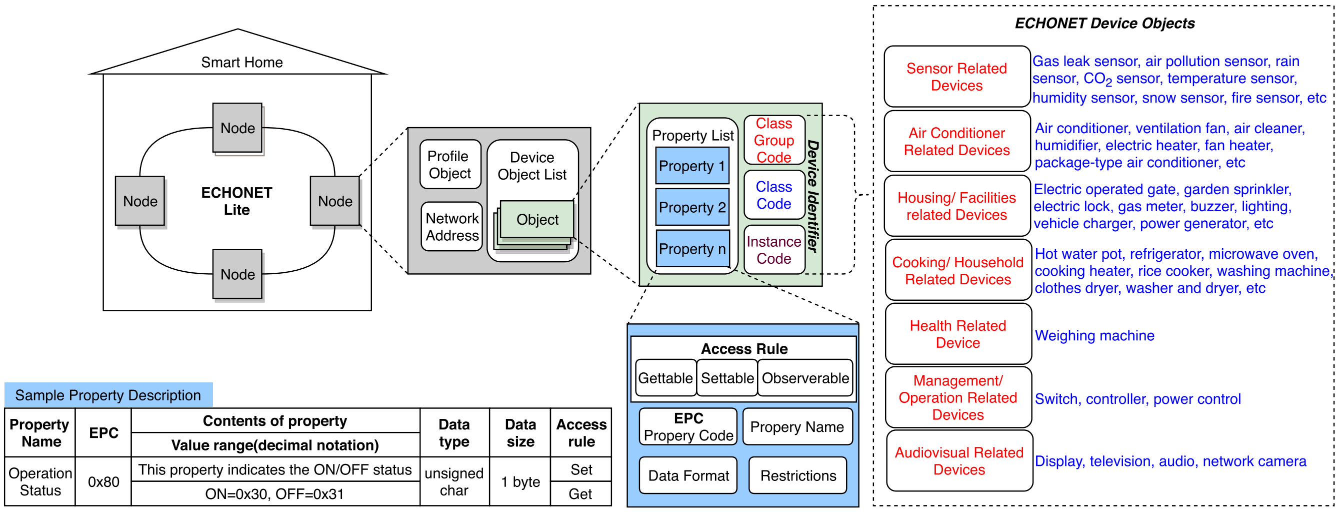

Fig. 1 Concepts of the ECHONET Lite protocol.

Table 1 ECHONET Lite SDK.

Name	Category	OS	Programming Language
SSNG	Tool	Window	-
SSNG for iPhone [11]	Tool	iOS	-
SSNG for Node JS	Tool	Window MacOS Linux	Node.js
echonet-lite	Middleware	-	JavaScript
library for Swift 3.0	Middleware	iOS	-
OpenECHO	Middleware	-	Java
Temperature Sensor EL	Emulator	iOS	-
Light Emulator -1	Emulator	Window MacOS Linux	Java

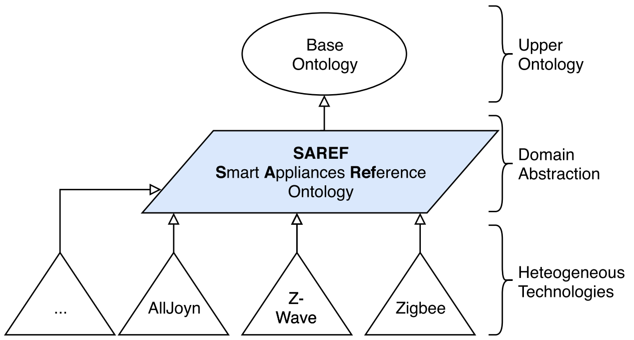

Fig. 2 SAREF Ontology Context.

work. Each node contains the *Network Address* and *Profile Object* which identify a node, and a list of *Device Objects*. A device object represents a logical device which is classified into seven groups and 108 classes of devices in the latest specification released in 2017 [10]. Device objects offer a standardized method to represent device resources and services via a list of *Properties* and corresponding constraints for each property.

2.2 Related Work

A list of ECHONET Lite SDKs referenced from Smart House Research center of Kanagawa Institute of Technology [*1] is summarized in **Table 1**. These SDKs provide tools and middleware which basically implemented frame translator functions and device interaction APIs to support sending and receiving frames in order to control ECHONET Lite devices in a simple manner. However, mechanisms to manage a network of devices have not been stated as well as the interoperability issues have not been mentioned.

In Ref. [12], a proxy which integrated ECHONET base smart home to PUCC [*2] protocol has been proposed. This implementation achieved interoperability at the communication level which was able to facilitate ECHONET Lite devices to service platforms (outside of the home network), however,the interoperability at the data level has not been introduced.

There was another effort from ECHONET consortium [*3] to map from the concept of device objects into smart device template (SDT) [13] to gain interoperability for ECHONET Lite devices. The SDT aims to provide an abstraction layer to describe appliance resources in XML format. XML is intuitively clear for human beings because tag names are able to provide semantic meaning, however, machines do not work that way due to the lack of intuition and consequently the usage of XML for semantic interoperability will be ineffective in the long run as stated in Ref. [14]. Therefore, the ontology model for ECHONET Lite specification is still desired.

In Ref. [15], SAREF ontology was proposed for the smart appliances domain. An overview of SAREF is illustrated in **Fig. 2**. SAREF is not intended to replace existing standards but to provide a domain abstraction model to link information from different technologies and domains for semantic interoperability based on ontology. The SAREF ontology becomes a part of ETSI [*4] standards [16]. There have been many extensions of SAREF to support ontology models for environmental devices, smart building devices, smart city infrastructure, and energy domain. There is no such a model for ECHONET Lite devices, thus an ontology model which is able to extend to SAREF is able to improve the

*1 http://sh-center.org/en/
*2 http://pucc.jp/
*3 https://github.com/ECHONET-Consortium/ECHONET-SDT-Contribution
*4 https://www.etsi.org/

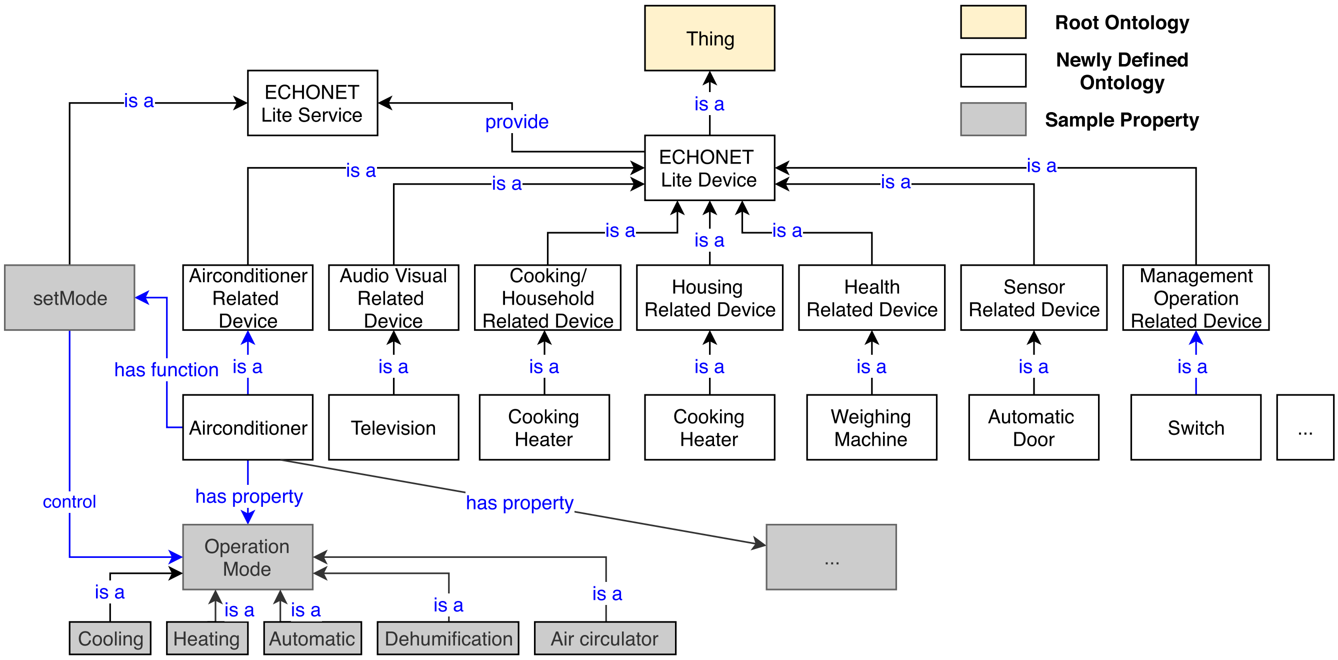

Fig. 3 Overview of ECHONET Ontology Model.

semantic interoperability for ECHONET Lite protocol.

3. ECHONET Ontology

Ontology was introduced to computer science in order to represent real-life concepts which are understandable by computers [17]. The ontology defines an information model to share a common understanding of knowledge and functionalities. The ECHONET Ontology (eOnt) is required to reflect the concept of ECHONET device objects including restrictions and enumerations based on RDF (Resource Description Framework) as shown in **Fig. 3**.

In order to improve the extensibility, *owl:Thing* is the root of the eOnt which is the most general concept and is easily replaceable by other domain concepts (e.g., *saref:Device*). The structure of the eOnt in Fig. 3 is different from ECHONET Lite device concept in Fig. 1 where the stating point of eOnt is the concept of *device object* instate of *node* and *node* information is a part of *device object*. These changes reduce the *subclassOf* mappings needed and shorten the implementation of a hierarchical mapping for the simple extension with other domains.

The eOnt fully supports 108 types of different devices in the latest ECHONET Lite specifications (English version, Release J, 2017) that includes vocabularies for device properties, relationships and constraints (mandatory or optional, data type and data range restrictions) of properties, and predefined enumeration values.

3.1 ECHONET Ontology Metric Analysis

During a research namely Smart Appliances funded by the European Commission from January 2014 to March 2015, a reference ontology model (SA Ontology) which supports ECHONET Lite specifications was introduced. The SA Ontology exploited ECHONET specification (Release C, 31 May 2013) which supports 89 different device types. The SA Ontology is being used as a reference for evaluation. The quantitative analysis of the eOnt has been calculated by exporting the ontology metric using Protege, a most widely used tool to create and modify ontology [18]. The metric of eOnt and SA Ontology is shown in **Table 2**.

Table 2 Ontology Metrics.

	SA Ontology	**eOnt** ECHONET Ontology
Axiom	945	**6,199**
Classess	188	159
Object Properties	27	**289**
Data Properties	2	**509**
Individual	35	**391**

Axioms support for the semantic interpretation of concepts and relations [19]. More axioms support more inference rules which can be used for automated reasoning. Numbers of *Data Properties* and *Object Properties* implies numbers of properties of a concept which has been mapped to the ontology. The coverage of the ECHONET device objects of the eOnt is better than the referenced ontology model. The number of *Individual* implies the number of mapped enumeration values. The eOnt also supports more individual to reflex predefined concepts of the specifications. The eOnt model is more comprehensive in the sence of providing semantic interoperability.

4. ECHONET Lite Adaptation Layer

An overview architecture of the AL is described in **Fig. 4**. The AL supports the semantic description of the network of ECHONET Lite devices by mapping device resources and services into RDF format resources using the eOnt model. This AL layer allows integrations between ECHONET Lite protocol with service platforms by implementing corresponding technology exporters which take the exported semantic resources as input for wrapper functions of specific technologies without any knowledge about the ECHONET Lite interface.

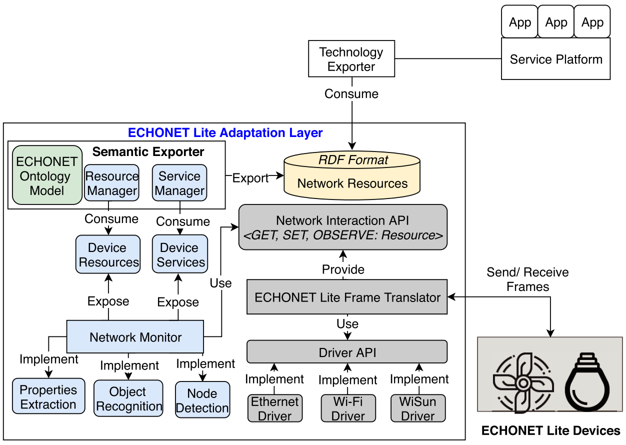

Fig. 4 ECHONET Lite Adaptation Layer Architecture.

EHD1	EHD2	TID	SEOJ	DEOJ	ESV	OPC	EPC_1	PDC_1	EDT_1	...	EPCn	PDCn	EDTn

```
- EHD1: ECHONET Lite message header 1 (1 Byte)
- EHD2: ECHONET Lite message header 2 (1 Byte)
- TID : Transaction ID (2 Bytes)
- SEOJ: Source ECHONET Lite object specification (3 Bytes)
- DEOJ: Destination ECHONET Lite object specification (3 Bytes)
- ESV : ECHONET Lite service (1 Byte)
- OPC : Number of processing properties (1 Byte)
- EPC : ECHONET Lite Property (1 Byte)
- PDC : Property data counter (1 Byte)
- EDT : Property value data (Specified by PDC)
```

Fig. 5 ECHONET Lite Frame Format.

4.1 Frame Translator

The ECHONET Lite protocol is defined at the application layer of the OSI model where network layer is based on Internet Protocols, the frame translator (FT) utilizes IP supported drivers such as Ethernet, Wi-Fi, or WiSun driver. The implementation of this FT module is heavily based on the frame format (**Fig. 5**) which is a part of the ECHONET Lite specification.

GET, *SET* operations are mapped to the corresponding value of the *ESV* and a *Resource* is described by a triple of *EPC* (property name), *PDC* (property format) and *EDT* (value).

4.2 Network Monitor

The main objectives of this network monitor module are to (i) obtain a list of ECHONET Lite nodes in the network, (ii) identify device objects in each node and (iii) recognize supported properties and extract property data in each object.

4.2.1 Node Detection

There are two ways to implement the node detection for ECHONET Lite network [20] (i) passively waiting for a message sent by nodes when they joined into a network or (ii) actively broadcast a node finding message at an arbitrary timing.

The first approach seems to support the real-time detection of the node without flooding the network with the node finding message. However, this approach is not feasible to apply in an entire running network because devices joined the network and they will not send the identification message again. This problem is solved by the second approach by actively asking nodes to send the identification message. However, in order to reduce latency for node detection, a high broadcasting frequency is desired and it increases overhead for the network.

To this end, the hybrid approach which only broadcasts the node finding message once at the starting time and passively waiting for messages from nodes is implemented to take advantages of both mentioned approaches. The node finding message is shown in **Fig. 6** with the *TID* is an arbitrary value as the transaction ID and *SEOJ*'s value is a node profile object (e.g., *0x0EF001*).

EHD1	EHD2	TID	SEOJ	DEOJ	ESV	OPC	EPC
0x01	0x81	-	-	0x0EF001	0x62	1	0xD6

Fig. 6 Node Finding Message.

4.2.2 Object Recognition

As stated in the ECHONET Lite specifications, a node must return a response with a list of device objects supported by that node. A device object has its identification which provides the device name. By the device name, supported properties, as well as property constraints of that device are defined at the specifications. However, in the specification, there are optional properties and these optional properties need to be identified by the *Property Extraction* module.

4.2.3 Properties Extraction

ECHONET Lite specifications require each device object to maintain a list of settable properties (*EPC 0x9E*), a list of gettable properties (*EPC 0x9F*), and a list of observable properties *EPC 0x9D*. Therefore device services and resources are extractable by sending frames with the corresponding *EPC*s to request the list of supported properties.

4.3 Semantic Exporter

This module uses the eOnt data model and device resources to serialize semantic resources in the RDF format which is a standard for semantically description of resources. An RDF statement is a triple of a subject, a predicate and an object. A subject is a resource, a predicate implies the relation between a subject and an object, and an object can be a resource or a data value. RDF statements can be linked to each other by using resources as objects. These resources are the object of one statement, then become the subject of another statement.

The *Service Manger* is responsible for creating resource described generic services for a class of devices which shares the same functionalities. The *Resource Manger* is responsible for creating device resources as a RDF graph.

ECHONET Ontology Model provides vocabularies which are used to semantically annotate device resources and services as RDF data.

4.4 ECHONET Lite Adaptation Flowchart

The AL monitors device properties data changed events and maps these changes into semantic resources as illustrated in **Fig. 7**.

In the ECHONET Lite specification, observable properties will notify the observer whenever a data changed event happened, thus these observable properties are easily monitored by implementing corresponding observers. For other properties, the AL has to store the old value and send multiple unicast messages to query data at an arbitrary timing.

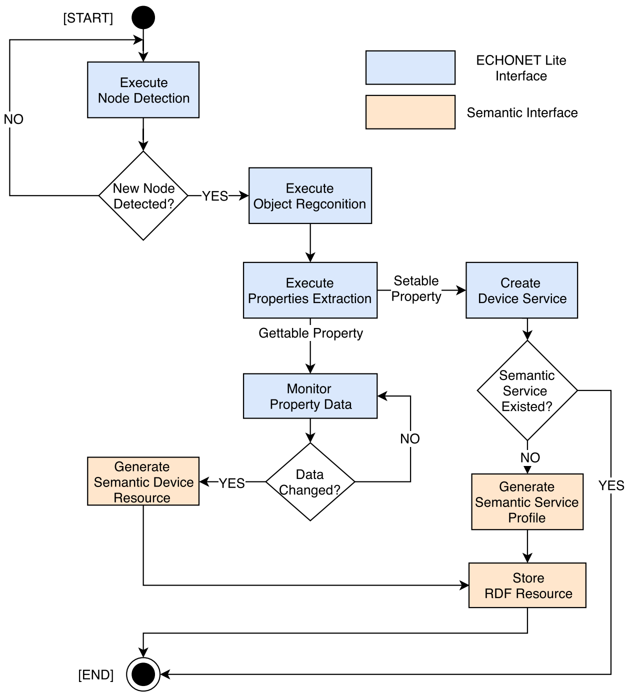

Fig. 7 ECHONET Lite Adaptation Layer Flowchart.

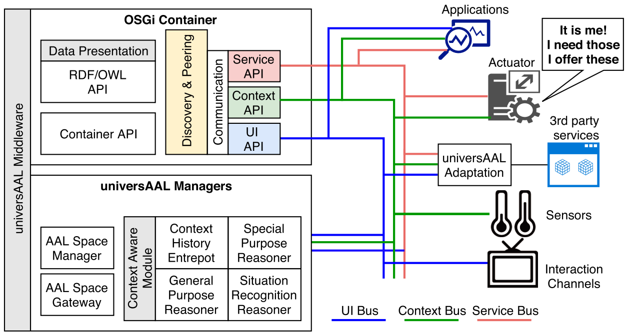

Fig. 8 The universAAL Platform.

5. Integration with universAAL Platform

5.1 universAAL Platform

universAAL stands for universal open platform and reference specification for Ambient Assisted Living and is the result of the European Union funded project to produce an open platform for the AAL. The uAAL platform allows the seamless integration of heterogeneous devices within a network environment through two base concepts: i) the usage of three communication buses for topic-based communication among components, namely a Context Bus, a Service Bus and a User Interface Bus; ii) the usage of ontologies for information and services sharing between components semantically. An overview of the uAAL platform is shown in **Fig. 8**. uAAL MW is the core component of the uAAL platform which encompasses the communication infrastructure of the platform. All devices that run this MW are nodes which can share knowledge and functionalities with other nodes in the form of ontology. The heart of this MW is formed by three buses and all the communication takes place via one of three following buses:

(1) Context Bus (CB) is an event-based communication channel to allow nodes to publish context events to the CB, regardless of the existence of recipients or not. Recipients are context subscribers which register their interest to the CB in order to only receive interested events.

(2) Service Bus (SB) is a call-based communication channel which allows nodes to request services from other nodes. Service providers are called service callees. They announce themselves by registering a service profile which describes their capabilities to the SB. The counterpart to service callees is service callers which send a service request through the SB to ask for a specific request.

(3) User Interface Bus (UI Bus) is used for delivering messages related to user interactions.

The uAAL is the most promising and holistic platform which directly benefits the end-user by being an affordable, simply configured, and personalized solution which also further empowers service providers by enabling easier and cheaper development of new AAL services or adaptation of existing ones. The uAAL has been widely used in European AAL projects such as inLife [21], ACCRA [22], Plan4Act, Plan4Act, OCARIOT, ReAAL, and Activage [23]. The idea of ECHONET and uAAL integration has been proposed in recent researches in Japan. In Ref. [24], the basic concepts and benefit of the integration were clarified, in Ref. [25], the integration layer including the ontology model has been clarified. However, detailed implementation, as well as the integration methodology, have not been explained. This integration is not only to validate the semantic interoperability of the proposed solution but also an effort to make the ECHONET Lite protocol available to European countries as well as support AAL services for ECHONET Lite smart home in Japan.

5.2 Implementation

There are two main approaches for the protocol-platform integration: *Adapter* and *Gateway* approach. However, there are a considerable amount of heterogeneous devices in smart home environments and the adapter approach requires one adapter for each device which the total hardware cost is extremely high. The ECHONET Lite - uAAL gateway (*elite4u*) is implemented for the integration.

The overall architecture of the *elite4u* which used the proposed AL to facilitate network of ECHONET Lite devices is illustrated in **Fig. 9**.

The elite4u has been implemented with the following characteristics:

- Seamless Plug and Play: When deploying the elite4u gateway into a network of ECHONET Lite devices, running nodes and newly joined nodes are discoverable. Resources and functionalities of discovered nodes are extractable and manageable. All devices are recognized and integrated automatically.
- Semantic Annotation of resources of the network of ECHONET Lite devices: Discovered logical device properties are mappable into semantic resources which are discoverable and understandable for the semantic level interoperability support.
- Ontology support: Ontology provides consistent meanings and relationships to describe resources which is the foun-

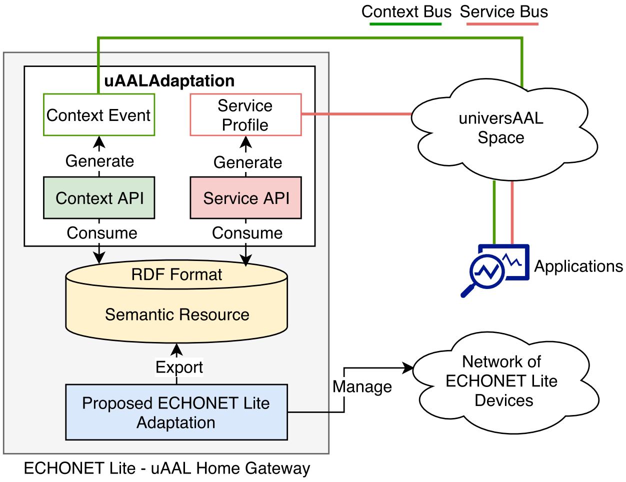

Fig. 9 ECHONET Lite - uAAL Gateway.

dation for the semantic annotation. The ontology must be comprehensive in order to reflect all attributes of a device without knowing device specifications.

Since the ECHONET Lite protocol does not provide facilities for UIs, the UI bus was ignored in this architecture. The elite4u exploits semantic resources of the network provided by the AL, classifies resources into knowledge into *Context Event* and functionalities into *Service Profile* to share in the uAAL space.

6. Experiment

6.1 Smart Home: iHouse

Experiments that have been conducted to test the implemented elite4u in the smart home supported the ECHONET Lite protocol. The experiment has been conducted at the iHouse located at Nomi city, Ishikawa Prefecture, Japan. The iHouse is an advanced experimental environment for future smart homes in Japan, and it has been implemented according to Standard House Design by Architectural Institute of Japan. The iHouse consists of sensors, electronic devices and home appliances that are connecting to each other by utilizing ECHONET Lite version 1.1 and ECHONET version 3.6. This configuration network emanates more than 300 sensors and actuators. The outdoor and the living room (experiment room) of the *iHouse* is shown in **Fig. 10**.

6.2 Experiment Configuration

All the tests have been carried out at the iHouse with the configuration as in **Fig. 11**.

The elite4u service gateway (GW) is deployed in the Karaf container which was configured as an uAAL coordinator node. The proposed ECHONET ontology and uAAL MW (v3.4.0) were installed in this Karaf container. The GW has two interfaces in order to interact with the ECHONET Lite network and uAAL space. The Robot Controller (RC) acts as a uAAL node with the same hardware and is configured as a normal uAAL node.

For the experiment, the identification *temperature sensors*, *air conditioners*, and *lighting devices* are recognized fro the interaction, other devices are detectable without identification. There are two use cases (UC) has been conducted. The actor of these use cases includes the *elite4u* service gateway, entire network of

(a) iHouse Outdoor

(b) ECHONET Lite Lighting Device (c) Peper Robot with Controller

(d) ECHONET and ECHONET Lite Adapter (e) iHouse Living Room

Fig. 10 Experiment Environment: iHouse and experiment devices.

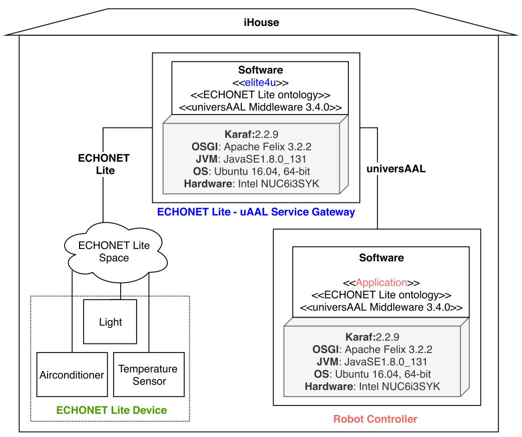

Fig. 11 Experiment Configuration.

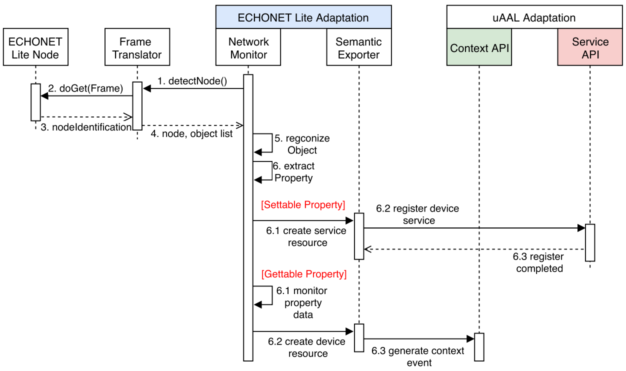

Fig. 12 Seamless Plug and Play Use Case.

Table 3 Node Detection Result.

	Total number	Total time for detection (ms)	Average time for detection (ms)
Node	85	564	~6.6
Device Object	252	581	~2.3

ECHONET Lite device in the iHouse and the RC.

6.3 Use Case 1: Seamless Plug and Play

The goal of UC 1 is to verify the operation of the elite4u when installing in the iHouse where the entire network of ECHONET Lite devices is operating normally. The purpose of this UC is to accomplish the following objectives:

- The elite4u GW is able to detect ECHONET Lite nodes and objects in the iHouse;
- The elite4u GW is able to extract and monitor properties of identifiable object;
- Extracted properties are able to be transformed into semantic resources (context events and service profiles);

The sequence diagram of the UC1 is shown in **Fig. 12**.

As soon as getting started, the elite4u queries connecting nodes of the network by sending node finding message to the multicast address at *224.0.23.0* for IPv4 or *ff02::1* for IPv6. Nodes must return a node identification message which contains a node profile and a list of objects managed by that node. Each object is a logical device and the name of the object can be identified by *Group Code* and *Class Code* as stated in the ECHONET Lite specifications. Attributes of the device are extracted as object properties where settable properties allow the interaction will be mapped to services and gettable properties are resources which must be monitored in order to get the latest status of the device. Device resources and services are semantically annotated by context events and service profiles of the uAAL respectively.

In order to verify the plug and play ability, numbers of node, numbers of detected object and the necessary time for this process have been summarized in **Table 3**.

Total time to detect network resources is **581 ms**.

6.4 Use Case 2: Device Service Interaction

The goal of UC2 is to verify the correct operation of elite4u service gateway when applying commands to devices by the following objectives

- The elite4u is able to register semantic device services exported by the proposed adaptation layer to the service bus.

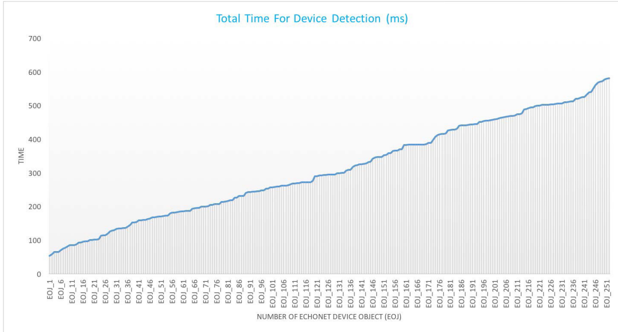

Fig. 13 Total Time For Device Recognition.

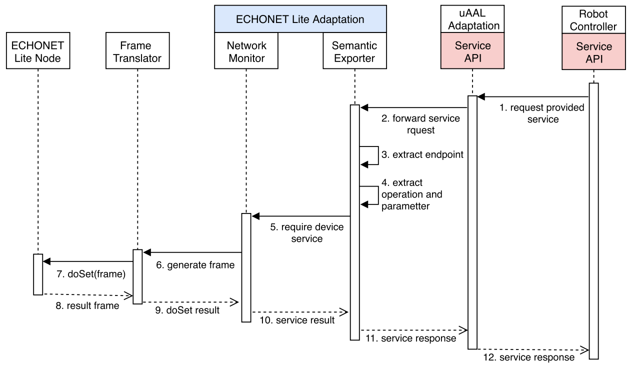

Fig. 14 Device Service Interaction Use Case.

- The registered services are usable for interacting with device.
- The elite4u is able to send commands to the corresponding device on the network.
- The elite4u is able to report results sent by the device to the requester.

Recalling the procedures of the elite4u when detecting a node, device services are identified by the access rule of properties. A mechanism to register abstract service profiles for devices which share the same functionality instead of registering separate service profiles for each device to reduce workload for the service bus was provided by the adaptation layer. The purpose of this use case is to measure the delay time caused by the adaptation layer including the time to identify the correct device to execute the request.

The sequence diagram of the UC2 is shown in **Fig. 14**.

The uAAL service bus supports a matchmaking mechanism to ensure the semantic discovery of provided services based on pre-registered service profiles and the delivery of service request to the service provider is guaranteed by the service bus (1).

As soon as a request is passed to the uAAL adaptation of the elite4u service gateway, the service request is forwarded to the semantic exporter (2) in order to extract corresponding endpoint (3), operation and parameters (4). After deciding the command, the corresponding ECHONET Lite device service provided by the network monitor module is invoked (5) and ECHONET Lite frames are generated (6). The *SET* operation API provided by the frame translator is called to forward the frame to the corresponding hardware (7). The ECHONET Lite device which receives the request (in the form of ECHONET Lite frame) executes the request and return the result frames (8). Based on the result frame,

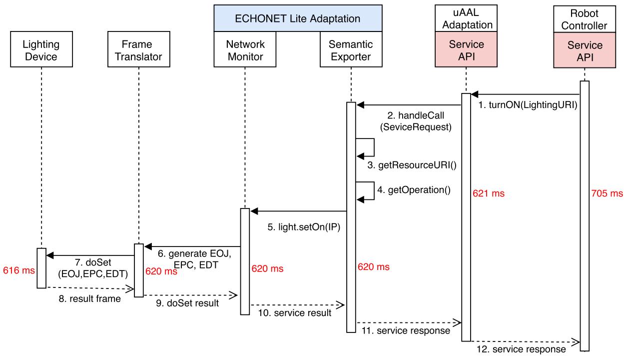

Fig. 15 Lighting Service Interaction Time.

a service execution result and a service response are generated accordingly (9), (10), (11). The service bus forwards the service response to the requester and terminates the interaction cycle (12).

An experiment which used the Robot Controller to turn on the ECHONET Lite lighting device (*Toshiba LEDD85021-LT1*) was conducted and the time is broken down in **Fig. 15**.

The necessary time for the light to execute the request is **616 ms** and the total time for an interaction cycle in the uAAL space is **705 ms**. The time added for the integration is **89 ms** which is consider a small amount of time. The added time caused by the adaptation layer is only **4 ms**.

7. Conclusion

This research proposes an adaptation layer for ECHONET Lite protocol based on semantic technologies. The proposed adaptation facilitated resources (device properties and functionalities) of a network of ECHONET Lite devices into semantic resources by introducing (i) a network monitoring mechanism to manage and networks of ECHONET Lite devices and (ii) an ontology model which is able to reflect the concept of ECHONET device objects. The network monitor implemented mechanisms to detect nodes, device objects, and device properties to support *seamless plug and play*. The proposed ECHONET Lite ontology is the foundation for supporting semantic interoperability. The ontology model is comprehensive in term of the coverage for ECHONET specification. The ontology model is able to extend with other domain ontologies (e.g., SAREF, oneM2M) to achieve a higher level of interoperability.

The service gateway based on the proposed adaptation layer which integrates the ECHONET Lite protocol into the uAAL platform was implemented. The wrapper for uAAL platform was created without taking care about ECHONET specifications by using semantic resources exported by the proposed adaptation layer. The delay time caused by the adaptation layer is small enough to prove the feasibility of the proposed solution. The implemented service gateway is the core component to support the interaction between the robot and smart environment in Ref. [26] as a part of the CARESSES project [27].

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