A New Layered Architecture for Future Big Data-driven Smart Homes

Mokhtari, Ghassem; Anvari-Moghaddam, Amjad ; Zhang, Qing

Published in:
IEEE Access

DOI (link to publication from Publisher):
10.1109/ACCESS.2019.2896403

Publication date:
2019

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Mokhtari, G., Anvari-Moghaddam, A., & Zhang, Q. (2019). A New Layered Architecture for Future Big Data-driven Smart Homes. *IEEE Access*, *7*, 19002 - 19012. Article 8629861. https://doi.org/10.1109/ACCESS.2019.2896403

IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received January 14, 2019, accepted January 28, 2019, date of publication January 30, 2019, date of current version February 20, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2896403

A New Layered Architecture for Future Big Data-Driven Smart Homes

GHASSEM MOKHTARI[1], AMJAD ANVARI-MOGHADDAM[2], (Senior Member, IEEE), AND QING ZHANG[1], (Member, IEEE)
[1]The Australian e -Health Research Centre, Brisbane, QLD 4029, Australia
[2]Department of Energy Technology, Aalborg University, 9220 Aalborg, Denmark

Corresponding author: Amjad Anvari-Moghaddam (aam@et.aau.dk)

ABSTRACT In this paper, a new layered architecture is proposed for big data-driven processing and management of future smart homes. The proposed Representational State Transfer (REST)-based architecture includes seven layers: physical, fog-computing, network, cloud-computing, service, session, and application for efficient data exchange and processing tasks of future smart homes. The smart home physical layer includes all the sensing technologies and smart devices within the smart home, which monitors the home environment and its residents. The data of these sensors will be sent to the smart home fog-computing layer that can do limited data storage and processing. Then, all the required data will be sent to the cloud-computing layer using smart home network layer. The cloud-computing layer provides the scalable solution for data processing and storage. The processed data in the cloud-computing layer will be provided as the data-driven services to different smart home and third-party (e.g., smart city) applications via smart home service layer. Based on the proposed architecture, the applications will utilize the session layer and RESTFUL APIs to use the data-driven services of the smart home. The proposed smart home architecture can provide a ubiquitous and shared data environment as the key aspect of Internet-of-Things systems.

INDEX TERMS Big data management, Internet of Things, smart home, layered architecture, data-driven services.

I. INTRODUCTION

The advances in digital technologies and internet of things (IoTs) has been instrumental in the upsurge of digital data generation [1]. Therefore, big data management and processing are a need for future digital systems to deal with the high volume of data for different areas such as health, energy, etc. Due to advances in data storage, processing, and communication technologies, it is now feasible to use the technologies to achieve benefits from different data-driven decision-making fields [2]. In other words, the technologies bring the capability to use data for different applications such as system monitoring, control, and optimization.

In the last three decades, there has been an extensive research work addressing solutions to data storage and processing. Data warehousing was the first solution proposed by Bill Inmon in 90s for relational data integration and processing [3]. Online Transaction Processing (OLTP) and Online Analytical Processing (OLAP) were the analytics provided subsequently via the data warehousing solution. However, there are several issues with data warehousing. Firstly, the solution is not an optimal solution for unstructured data. Additionally, the cost associated with this solution is high [4].

In order to deal with the issues regarding data warehousing, distributed file storage and processing platforms such as Hadoop was proposed. Hadoop is an open access solution proposed by Doug Cutting and his colleague Mike Cafrella in 2005 [5]. The main objective of Hadoop was to provide reliability and scalability in data processing. This framework provides a platform to store and analyze unbounded big data on a group of computers (clusters). The suggested distributed environment provides high data storage capabilities. Additionally, multiple clusters provide the parallel processing capability which is a promising solution for high-speed processing of high volume data.

The advances in distributed file storage and processing systems in recent years have provided more capabilities to deal with big data and IoTs challenges. Additionally, cloud technology can also provide a cheap, flexible and scalable big data solution for data storage and processing.

The associate editor coordinating the review of this manuscript and approving it for publication was Chin-Feng Lai.

Smart home as the core of future IoT systems and data generation for various applications such as health and energy needs proper data management and processing paradigm. The smart home concept was firstly proposed in [6] for energy management purposes. There are several works listed in the literature which use data from different energy resources and they scheduled these resources to optimize the energy consumption [7]–[9]. In all these studies, a standalone energy management system was used to collect data from the local resources in order to optimize their operation. However, as the number of the sensors in the smart home increases, there will be a limitation on storage and processing capabilities in the smart homes. Moreover, smart home devices from different vendors and firmware may have interoperability issues, which is an important challenge of future smart homes [10]. Recent literatures have reported researchers working on different middleware solutions to deal with this challenging problem [11]–[17]. As an example, [11] presents a middleware with both machine-to-infrastructure (M2I) and machine-to-machine (M2M) capabilities which bridges the gap between the heterogeneous device semantics and a common interface for merging protocol variations. Tao *et al.* [13] elaborate on a scheme for ontology-based data semantic management and application where a general domain ontology model is designed by defining the correlative concepts. A logical data semantic fusion model is designed accordingly and the performance of the proposed structure is demonstrated using a group of elaborated ontology data query and update operations. To supporting various connectivity and faster transmission, a hybrid computing model based on fog and cloud computing (called Foud) is proposed in [14] where, different from previous proposals, fog computing is integrated into Foud as a sub-model of temporary fog, owing to the dynamic of mobile computing resources. To cope with the issue of the tremendous data exchange, 5G communication technologies are also utilized. To enable effective communication among warehouse objects over the web, [15] presents a web-oriented architecture using REST framework in which the smart warehouse consists of a data collection module and an administrative module. Likewise, by using a web-of-objects (WoO) and cloud architecture, [16] proposes an interoperable IoTs platform for a smart home. The platform is able to control in-home appliances from anywhere and to provide the homes' data in the cloud for various service providers' applications and analysis. A similar semantic functional module for user centric service composition in WoO platform is proposed in [17] where an ontology model for virtual object is also considered. However, the major drawbacks of the previous works are obviously the interoperability issue, local storage and processing capabilities that cannot be unbounded to deal with big data generation and processing.

On the other hand, although the reviewed data management and processing paradigms demonstrate acceptable performance in a given application, they lack proper data handling features in multi-functional environments such as smart homes where a developed architecture should interpret and process the sensed and measured information from different nodes (e.g., health- and energy-related domains). In such situation, interoperability of various devices with different communication technologies cannot be easily supported and security and privacy issues may be raised in implementation and realization phase.

To overcome these issues, a scalable architecture is proposed in this paper to facilitate unbounded big data management and processing of smart homes. The proposed REST-based architecture includes seven layers; physical, network, computing, service, session and application which can provide a scalable solution. Additionally, common standards are proposed for data format and exchange methods based on RESTFUL APIs to provide a shared data environment in smart home for extensive interoperability in this system. The main contributions of this paper can be summarized as follows:

- A flexible and scalable architecture is proposed for different applications in smart homes to facilitate unbounded big data management and processing,
- A common standard based on RESTFUL APIs is proposed for data format and exchange to enable interoperability of various devices and constrained IoT devices,
- Security features are embedded in the proposed layered architecture (mainly in the application and service layers) for authorized user access and reliable data exchange.

The rest of paper is organized as follows. Section II is related to the proposed smart home architecture. To show how the proposed structure could fit in different applications in the current and future smart homes, several use case are introduced in section III. Discussion and conclusion remarks are finally drawn in section IV.

II. PROPOSED SMART HOME ARCHITECTURE

In recent years, extensive research works have been conducted on data processing challenges, addressing various smart home applications such as energy and health. The main objective of smart home is to provide a better quality of life to its residents [18]. As noted earlier, the smart home was firstly proposed for the application of energy automation and management. However, other applications such as health monitoring and security were introduced later as part of this platform [19]. A significant portion of the current research studies are related to IoTs and the challenges with big data generation and processing. Many of the smart home research studies are on the specific and individual type of applications, like health or energy monitoring in the smart home [7], [9], [19]. The current research observations lead us to a need for a global and comprehensive architecture dealing with the big data collectively relating to all different smart home applications. The solution should provide an interoperable, ubiquitous and shared data environment essential for IoTs system. The aim of this paper is to propose an architecture that comprises of the elements of such environment for smart home platform.

The architecture, given in Fig. 1, is proposed for data-driven IoTs system within smart cities. In any smart IoTs system such as smart home, smart grid, smart transport, etc., this architecture can be used to provide shared data-driven processing and decision-making. In order to explain the proposed architecture in more details, this paper uses the smart home as the core of data generation and smart IoTs systems.

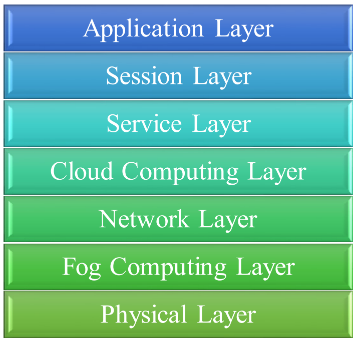

FIGURE 1. Proposed layered architecture for future IoTs systems.

The proposed layered architecture is mapped to the smart home application and is shown in Fig. 2. The details of each layer in the proposed architecture are as follow:

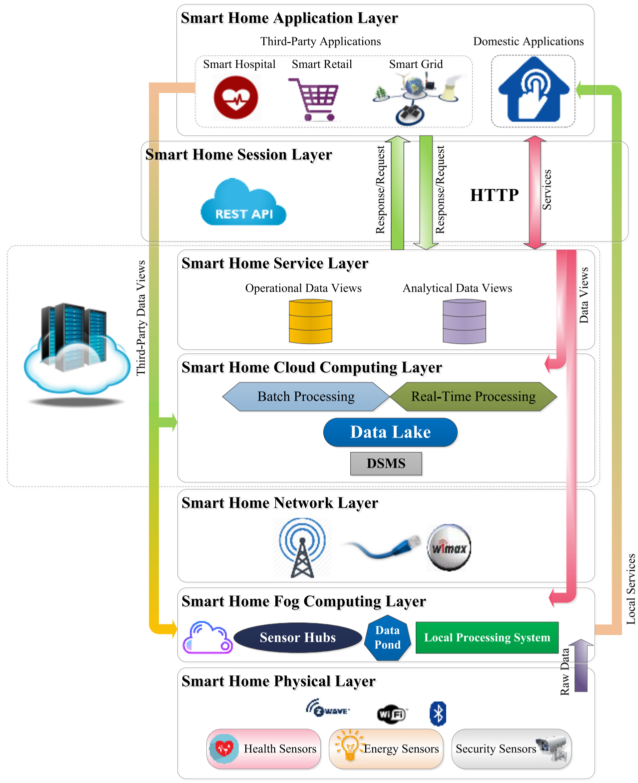

FIGURE 2. Proposed layered architecture for the smart home.

A. SMART HOME PHYSICAL LAYER

The first layer in the proposed architecture is physical layer. As shown in Fig. 2, the smart home physical layer includes three main types of sensing technologies and devices installed at home to monitor resident's health status, energy consumption, etc. These sensing technologies with their details are listed below:

1) SMART HOME HEALTH SENSORS AND DEVICES

The high demand in healthcare system introduces lots of challenges and costs for the governments, as the main entity responsible for public health in the society. In order to deal with these challenges, an effective approach can be provided through in-home telehealth monitoring systems [20]. Smart home and wireless sensor network (WSN) have promising features to provide such a platform that can monitor people activities and physiological signs and detect abnormal events without any physical attendance of caregivers. There are two main tiers of sensors for health monitoring in the smart home. The first tier includes activity sensors such as motion and power sensor to detect resident Activities of Daily Living (ADLs). There are two main types of activity sensors for smart home applications. The first type is environmental activity sensors, which are technologies such as motion sensor, installed around the home setting, and not intruding on any privacy and place any burden on resident's lifestyle [21]. The second type of activity sensor includes wearable technologies like accelerometer or gyroscope which needs resident's participation to wear the sensors at all times to monitor their physical activities like sitting, standing, etc. The second sensor tier in smart home health monitoring system includes the physiological sensors which monitors the vital signs of residents. This sensor tier also includes two main categories as wearable and environmental.

2) SMART HOME ENERGY SENSORS AND DEVICES

As noted in the introduction section, the primary goal of the smart home is to provide efficiency and automation in home energy system. Smart home Energy Management System (EMS) is responsible for efficient energy scheduling at home. Sensing and monitoring the status of energy devices is the key part for this application. Smart home energy sensors can be categorized into the following tiers:

- Smart appliances – there are multiple types of smart appliances in homes. Typical smart appliances to be scheduled for various energy management plans can be included as laundry, dishwashing machines, etc. [22]–[24]. Data from these devices including their status (ON or OFF) and their parameters need to be sensed and sent to the upper layers for further processing.
- Comfort system – Lights in smart homes can automatically become ON, OFF or dimmed to provide an efficient living condition for residents. Additionally, temperature in smart home can efficiently be adjusted using heating/cooling systems [25]. However, to control the lights and temperature based on resident's presence mode and preferences can be included using sensing

technologies such as occupancy sensor to detect the information and adjust the devices accordingly.

- Local energy generation – It is expected that local generation will play an important role of energy platform in smart homes. The environmental data related to local generation such as weather data, generation status, generated power, etc., need to be sensed and sent to the computing layers for efficient energy management in the smart home.
- Electric vehicle – Electric vehicle is also considered as a key part of energy platform of future smart homes. They can charge and discharge their power based on home energy management plan requirements. Therefore, the data especially the state of charge needs to be sensed and communicated to the upper layers.
- Energy Meters – Measuring and monitoring the electricity consumed in the home can provide beneficial information such as electric usage behavior which is beneficial for both smart home and smart city applications. Energy consumption monitoring can be done through both single point and distributed sensing. In single point sensing, we use only one single smart meter in home electricity box which monitors all the energy usage of home [26]. However, distributed sensing consists of distributed smart metering around the home.

3) SMART HOME SECURITY AND SAFETY SENSORS [27]

- Fire sensors – Smart home fire detection system includes fire sensor that checks the carbon monoxide level. In the event of fire, this sensing system can send the data to the upper layers for further processing and action including notification to the fire station, etc. Further processing of the data could be used to locate the specific area of the fire.
- Access sensors – The security access devices are used to determine and distinguish residents and visitors from intruders. These sensors include several types of technologies as camera, fingerprint, security code, etc.

B. SMART HOME FOG COMPUTING LAYER

The proposed architecture includes both fog- and cloud-computing layers for better scalability and flexibility. There are some light computing tasks which can happen at the edge. So, the fog-computing layer can provide this capability while skipping the data communication to the cloud-computing layer. In other words, fog-computing provides a scalable solution for cloud computing which provides storage and computation close to the end devices. In order to attain a near real-time response for some processing tasks which do not need cloud capabilities, fog computing is considered in the proposed architecture close to end devices which can minimize latency. It can also reduce the data transfer traffic to the cloud.

In the proposed architecture, fog-computing layer includes sensor hubs which do some simple data processing such as data concentration and schema mapping to the sensor data. We consider a local data storage as a data pond of smart home which can provide limited data storage for local smart home applications. There is also a local processing system which can run local data processing tasks and provide local services to smart home applications.

C. SMART HOME NETWORK LAYER

Smart devices in smart homes usually come from different companies and do not use a single communication protocol to communicate their measurement and sensing data. This is the main reason of interoperability issue in smart home. As these smart devices cannot communicate with the same protocol, interoperability, and M2M communication is the main challenge within the future smart home with smart devices from multiple manufacturers. However, as all these devices ultimately can connect to internet, either directly or through their hub, it is proposed that M2M communication can be done through the cloud [28]. In this case, the sensor or a device sends its data to the cloud-computing layer and the data are transformed to a specific common format that are understood by all devices and applications. To transfer the data to smart home cloud-computing layer, smart home network layer should be used.

The network layer includes smart home gateway and communication protocol such as Ethernet, cellular and WI-MAX that are used to transfer the data to the cloud-computing layer for further processing. There are also some new communication network technologies such as Long Range (LORA) that can send sensor data directly to the cloud computing layer, considered also as a technology in smart home network layer [29].

D. SMART HOME CLOUD COMPUTING LAYER

Cloud computing layer provides the required extensive computing which cannot be implemented at the edge. The proposed structure for smart home cloud computing layer is shown in Fig. 3. The layer includes Data Stream Management System (DSMS), Data Lake, Real-time processing system and Batch processing system. The details of each part are listed in the followings.

1) DATA STREAM MANAGEMENT SYSTEM (DSMS)

In smart home physical layer, we have several types of sensors that generate continuous, ordered, large and unbounded

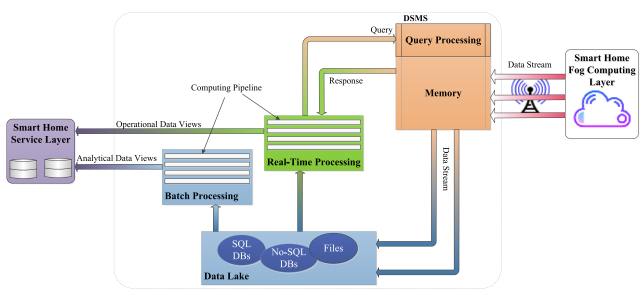

FIGURE 3. Cloud-computing layer of the proposed smart home architecture.

sequence of data record as measurement data stream. Therefore, to deal with this high volume and high velocity data, smart home computing layer needs to be supported by a DSMS to deal with continuous data generation and quarries. DSMS provides the capability to do an online analysis of this fast-changing data as shown in Fig. 3. This system is able to store data to the Data Lake while having the ability to handle the real-time queries.

To illustrate, we have hundreds of sensors which generate streamed data events with payload data as given in Fig. 4. The sensor hub pushes these data events to cloud-computing layer. The DSMS is responsible for ingesting the streamed data and running the real-time quarries. A very simple SQL query can be like the one below, which put the data in output.


```
{
  "timestamp": "20190127124357",
  "dsp": "tempsensor",
  "temp": "28"
}
```


FIGURE 4. JSON format of sensor data.

2) DATA LAKE [30]

In conventional data center and warehousing systems, data needs to have a specific and pre-defined schema. However, there are several issues with this. Firstly, adding schema to the data usually takes a lot of time. Additionally, the way to process data should be defined at the time of schema definition. The last but not least, some data do not fit to the predefined schema which needs to be disregarded. Therefore, to deal with this issue, central data storage is needed to provide capacity to store data in any format in a cost-effective manner. This enables us to add the schema to those raw data when it is needed during the data processing. Data Lake, in the proposed structure, includes all types of storage and databases as shown in Fig. 3. This provides the capacity to store the data in any format, which is so important for data science purposes.

3) REAL-TIME DATA PROCESSING SYSTEM

In the proposed set-up for the computing layer, the real-time data processing system has the main data processing task. It provides the capability of data processing for real-time applications such as optimizing the smart home energy, appliance scheduling, anomaly detection, etc. This system takes advantages of multiprocessing capability to allow processing of data-driven tasks efficiently. As real-time action is needed, the latency should be in the range of milliseconds while having the ability to run different concurrent tasks.

The real-time data processing system includes several types of computing pipeline which feeds data from smart home DSMS, data lake, and service layer and output operational data view to smart home service layer as shown in Fig. 5. Operational data views are used as the services

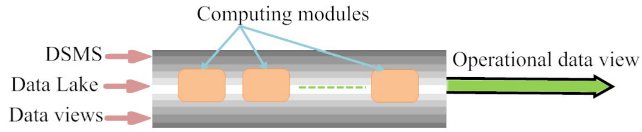

FIGURE 5. Real-time data processing pipeline.

for different smart home applications such as optimal energy management and device control.

4) BATCH DATA PROCESSING SYSTEM

Batch processing will accommodate analyzing massive and complex behavioral sets of data. Data-driven tasks such as behavior and preference modeling of the residents that needs historical data processing can be considered to be executed through batch data processing pipeline as shown in Fig. 6. As there is no real-time processing needed for this system, the latency of the processing entity can be in the range of minute with the capability of multi-task processing as well. The results of batch processing systems can be available as analytical data views in the service layer.

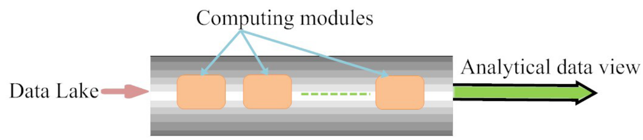

FIGURE 6. Batch data processing pipeline.

E. SMART HOME SERVICE LAYER

Processing the whole or part of smart home dataset with a specific query function is very challenging as it needs huge processing time. The best solution to deal with this challenge is to preprocess the queries and make it available as views. Then these views can be accessed very quickly whenever they are queried. In the proposed smart home architecture, it is proposed that all the data-driven services from computing layer should be available at service layer through specific metadata format as smart home data view. A standard data format for these services can help to provide a shared data environment for all authenticated applications within the smart home or smart city to use these services.

Service layer includes two main types of data views as: operational data views and analytical data views. These data views are explained in the following.

- Operational data views are the outputs of real-time data processing pipelines in computing layer. Device views are one of the main types of operational data views to provide the data related to status and parameters of different devices. If any application within smart home or smart city aims to control a device or change its status, it can be done through device view which can be updated by the application. Additionally, M2M communication can be done through these views in smart homes.

- Analytical data views are the output of batch data processing pipelines which preprocess the historical data of smart home and provide those as service in smart home service layer for applications within the smart home or smart city.

There will be also third-party data views which are provided by smart city applications, such as smart grid, smart retail, etc. For instance, the electricity price or the weather data can be provided as third-party data views to smart home computing layers and be used for different computing tasks such as optimizing the energy of smart home.

As noted before, a standard data format should be considered for these data views to provide shared data environment. These views or resources can exist in different formats such as XML, JSON, etc. As an example, the XML format for a Device view is shown in Fig. 7. This view includes 4 attributes for a device as its HomId of 5, HubId of 1 and with the value of 15. There are other attributes that can be added to this view which depend on the device and its technology. However, these attributes for each type of device in the smart home should be standardized.

```
<?XML version="1.0" encoding="UTF-8"?>
<DeviceView>
<HomeId>5</HomeId>
<HubId>1</HubId>
<DeviceId>30</DeviceId>
<Value>15</Value>
</DeviceView>
```

FIGURE 7. Example of a device view.

F. SMART HOME SESSION LAYER

In the proposed smart home architecture, the session layer is responsible for providing standard and APIs to exchange data between smart home service and application layers. Due to limited capability such as energy limitation, it is not possible to have a continuous connection between application and service layers [31]. The proposed REST-based architecture can use RESTFUL APIs and URL-based communication which can provide a good solution for this issue. A REST-based architecture has six constraints including uniform interface, stateless, catchable, client-server, layered system, and code on demand which are all satisfied by the proposed architecture [32]. Therefore, RESTFUL methods can be a good option for data exchanges. As these methods are based on hypertext transfer protocol (HTTP), we do not care about the type of interface or application which uses these methods and exchange data with smart home service layer. In REST-based system, resources (smart home data views) are identified by URL. To provide a scalable solution for the resources, the URL should represent the hierarchy. As an example, Table 1 shows this hierarchical structure in hubs and sensors.

The HTTP methods are used to create (CREATE), read (GET), update (PUT), delete (DELETE) resource in the server (service layer). As a result, the resources should be designed based on REST architecture. When an application (as a client) sends a request (GET, PUT, etc.) to the service layer (as a server), the session layer parses the resource information and if this session is legal and authenticated, it will find the resource (view), encapsulate and provide that to the application. Table 2 provides examples of these types of request.

TABLE 1. Hierarchical structure of device views.

Resource name	URL
Collection of hubs	/hubs
Specific hub	/hubs/{hubId}
All devices under hub	/hubs/{hubid}/devices
Specific device under specific hub	/hubs/{hubid}/devices/{deviceid}

TABLE 2. Example of request in session layer.

URL	Method	Description
/hub	GET	List information about all the hubs in smart home
/hub/hubId	GET	Display information related to hubId
	PUT	Update information related to hubId
/hub/hubId/deviceId	GET	Display information related to deviceId
	PUT	Update information related to deviceId

G. SMART HOME APPLICATION LAYER

The smart home application layer includes all the applications which are subscribed to use or exchange data-driven services of smart home. These applications can be categorized into two main classes:

1) SMART HOME DOMESTIC APPLICATIONS

The main aim of the proposed smart home architecture is to provide the data-driven services to the applications within smart home. In this structure, there are several types of applications such as device control, EMS, etc. within smart homes which can use these services.

2) SMART HOME THIRD-PARTY APPLICATIONS

The proposed architecture can also provide this capability to exchange data-driven services with third-party applications within smart city such as smart grid, smart hospital, smart retail, etc.

III. USE CASES

In this section, we introduce two smart home platforms, which are used as use cases to show the current stage of research and development in smart home applications. As health and energy are the main smart home data-driven applications, CSIRO Smarter Safer Home (SSH) and Alborg University (AAU) Energy Internet platforms are introduced as an example of each application. The details of these platforms are listed below.

A. SSH PLATFORM

The objective of the SSH platform is to support independent living of seniors, enhancing their life quality. Through collecting objective information about the residents' activities, the ADLs of elderly people can be assessed automatically. To achieve this objective, SSH platform utilizes data from wireless sensors deployed in the home environment, and automatically infer health related activities through human behavior detection. Fig. 8 shows the structure of this smart home platform based on the proposed architecture. There are several types of activity and vital sign sensors used in the physical layer of SSH platform. Table 3 illustrate some of the collected data in this platform. There is motion sensor installed in each room which can detect the location and transition of resident in different rooms. Power sensor, which is plugged to the electricity outlet, can measure the electricity consumption of the attached device. Temperature/humidity sensor can detect the changes in air condition and related activities in kitchen and bathroom. Accelerometers are also used to detect the door movement (opening/closing) of fridge, microwave, etc.

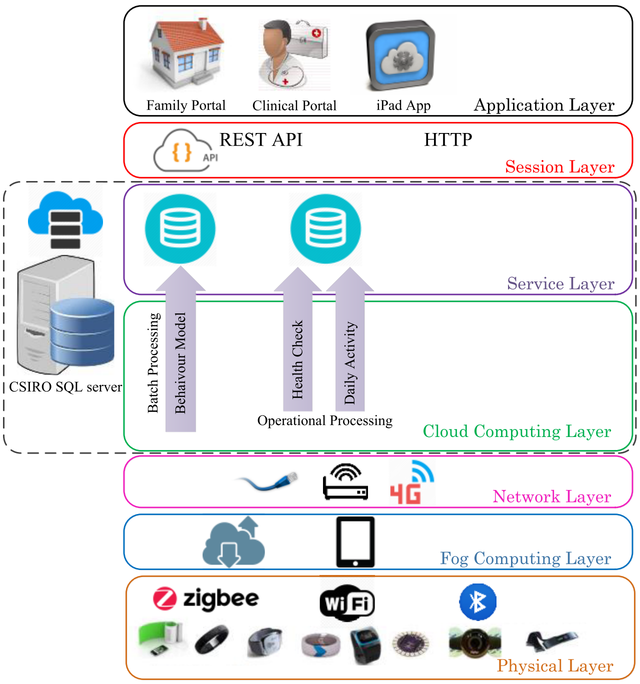

FIGURE 8. SSH platform to provide independent living for elderly.

TABLE 3. Examples of smart home sensor data.

Sensor ID	Sensor type	Timestamp	Value
15	Motion	2018-10-05T05:12:00	1
31	Power	2018-10-05T05:23:00	0.239
15	Motion	2018-10-05T05:41:00	1
148	Humidity	2018-10-05T05:49:00	58%
148	Temperature	2018-10-05T05:49:00	18.3 C
177	Accelerometer	2018-10-05T05:54:00	1

Table 4 also lists vital sign sensors which are used in this smart home platform. There are three communication protocols which are used by the sensors to transfer their data to the sensor hubs. In-home sensors use low-power ZigBee communication for data transmission. Vital sign sensors use Wi-Fi to transmit to an iPAD as the sensor hub. Additionally,

TABLE 4. Vital sign monitoring in SSH platform.

Sensor	Description
Scale	Measuring resident weight
Blood pressure	Measuring resident blood pressure
Thermometer	Measuring body temperature

accelerometer sensors use Bluetooth Low Energy (BLE) to communicate entrance door data to their hub.

Collected data by the sensor hubs are communicated to the CSIRO data center via home gateway and are initially processed in SQL-based databases to extract meaningful information such as appliance usage, room transition, etc. Specifically, activities related to resident's mobility, bathing and meal preparation could be extracted in this platform. The domains of ADLs are presented to be intuitive to the resident and carer on the SSH platform, as illustrated below in Figure 9(a).

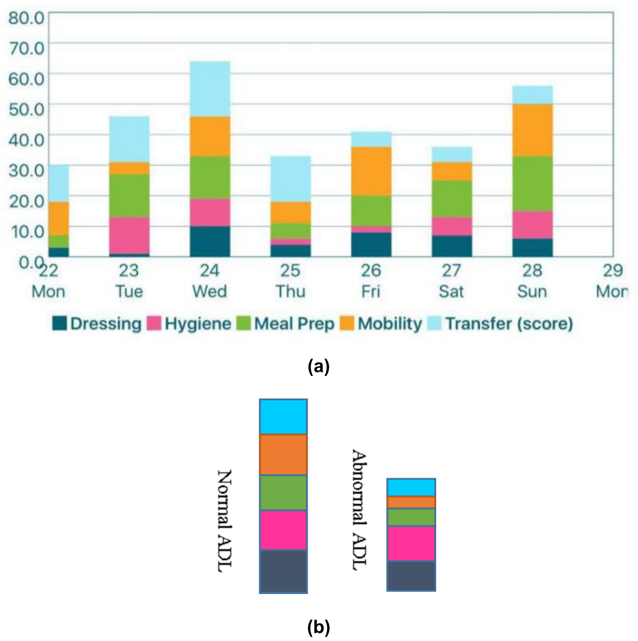

FIGURE 9. (a) ADLs assessment for a week, (b) normal and abnormal ADL.

If the left stack bar in Fig. 9 (b) shows the normal functional status of the senior person, the ADLs is shown on the right bar in Fig. 9(b) may be a symptom of health status changes, should it recur more regularly. A medical consult with clinicians would therefore be recommended. Different components and information of the SSH platform including family portal and clinical portal could have access to the data of this smart home platform. These applications use RESTFUL methods to access the data-driven services.

B. AAU ENERGY INTERNET PLATFORM

The second use-case in this paper is AAU Energy Internet platform which is developed for energy management in residential buildings. As shown in Fig. 10, the Energy Internet platform introduces a hybrid AC/DC platform with different means of local generation (such as wind turbine

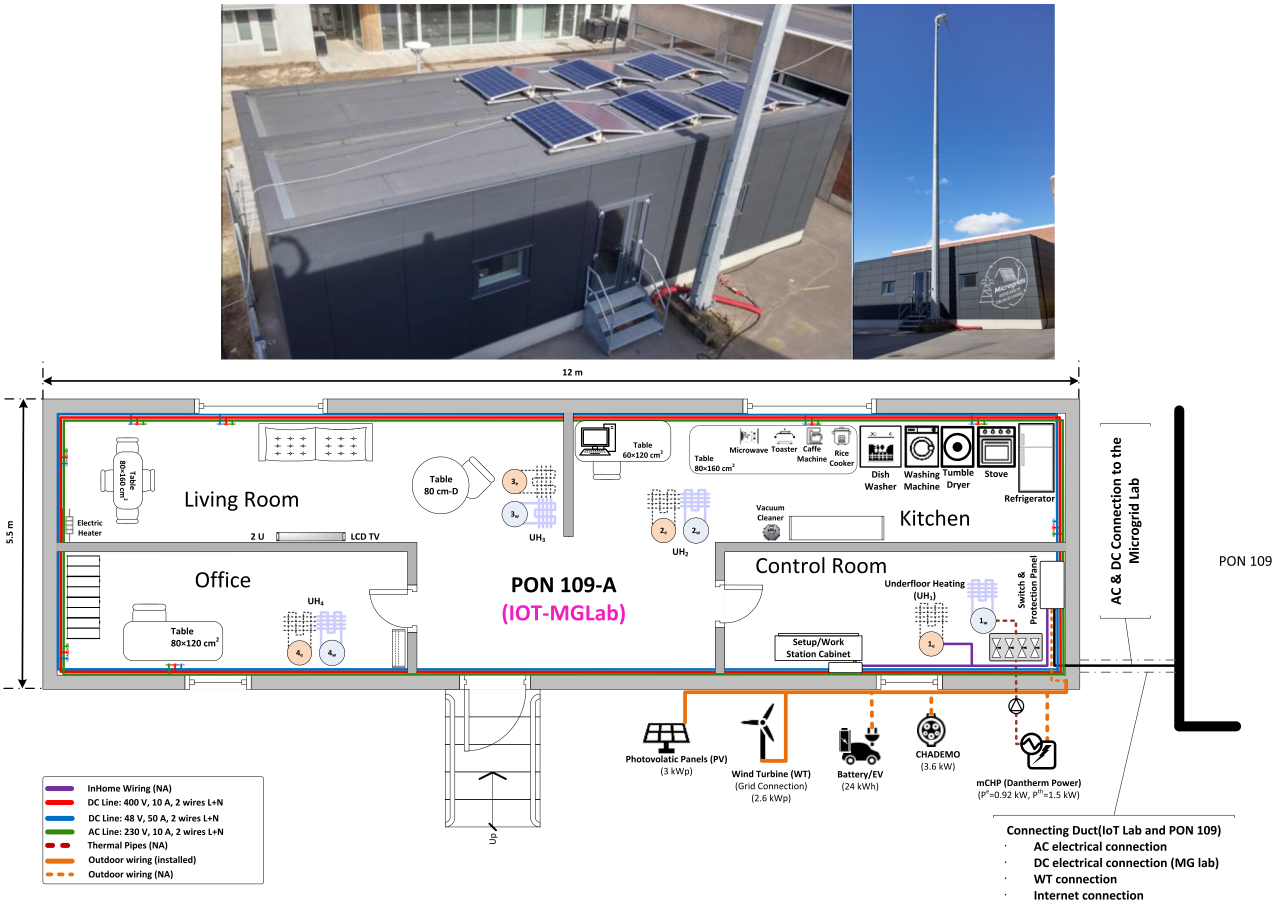

FIGURE 10. Energy Internet platform – Aalborg University (AAU).

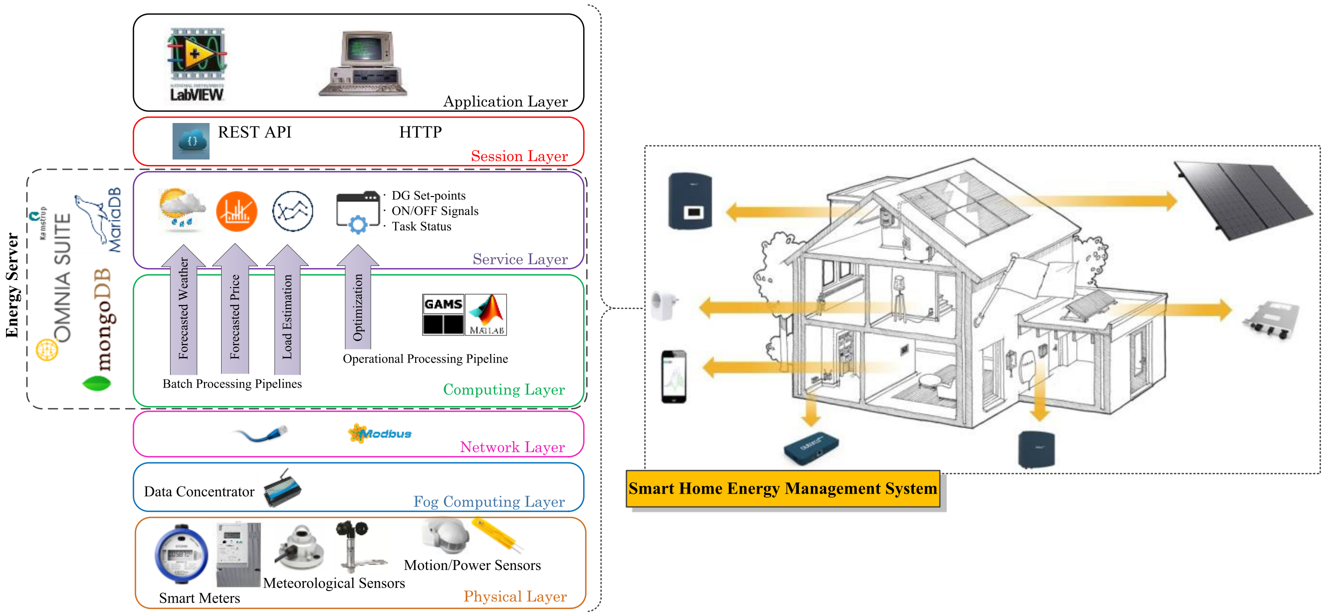

FIGURE 11. Architecture of the proposed smart home energy management system in AAU Energy Internet platform.

(WT) and roof-top photovoltaic (PV) panels) and energy storage as well as controllable loads (e.g., washing machine, tumble dryer, freezer, etc.). Moreover, the platform provides practical, optimized and comfort-aware energy management solutions for residents using real-time control and monitoring systems.

As depicted in Fig. 11, the physical layer in this platform includes smart meters, meteorological sensors and activity sensors such as motion sensor. These sensors and devices use different communication protocols including Wi-Fi, Bluetooth and Zigbee to communicate their data to a data concentrator as their hub [33]. The data concentrator adds required structure to the sensor data and record those in the energy server databases including MongoDB, MariaDB and Omnia Suite. The computing layer in this smart home platform includes MATLAB and GAMS solvers which are used by different batch and operational pipelines. There are three main batch pipelines in this energy platform including weather forecasting pipeline, electricity price forecasting pipeline and load forecasting pipeline. The weather forecasting pipeline uses metrological sensors data to estimate the power output of WT and PV systems for short time intervals (e.g., 5min to 1h resolutions).

The price-forecasting pipeline uses the recorded information of price for tracking the energy price trend in coming period. In a similar fashion, the load estimation pipeline uses the smart meter's data records to better forecsat the residential base load.

The operational pipeline in this smart home platform is the EMS pipeline that controls the operation of in-home devices and appliances optimally with regards to different objectives (e.g., minimizing energy costs and maximizing comfort level) considering the information about task operating status, user's requests and network signals received through the AMI system (such as energy prices and meteorological information). The EMS could also use the information about presence of people over a period of time and accordingly extract occupancy model of residents. This would help the system better manage activities within the scheduling period. To keep a meaningful balance between the energy saving (Obj_1) and a comfortable lifestyle (Obj_2), EMS should solve a multi-criteria decision making problem as [34]:

$$Obj_1 \left\{ Min.\ ECC = f(RTP,\ GP,\ P_g^t,\ P_{DG_i}^t) \right\} \quad \forall t \in T,\ i \in N_{DG} \qquad (1)$$

where ECC denotes the energy consumption cost of a typical residential building which is a function of power exchanged between the building and the utility at time $t(P_g^t)$, power produced by domestic generation unit i (P_{DGi}^t), and the real-time grid electricity and natural gas prices, respectively (RTP and GP). Moreover, the second objective which is formed based on the user's convenience level about household task scheduling (TSC) and thermal comfort level (TC) can be modeled as follows:

$$Obj_2\ \{Max.\ \ CL = f(TSC, TC)\} \qquad (2)$$

$$TSC = \sum_{t \in T} \sum_{j \in M} (\omega(j) SL(t, j)); \quad TC = \sum_{t \in T} CL(T_{in}(t)) \qquad (3)$$

where, $SL(t,j)$ is the user's satisfaction level when task j is executed at time t and $CL(t)$ is the level of thermal comfort (regarding the indoor temperature T_{in}) observed by the inhabitants at each time step.

The output of this pipeline which includes the set-point of smart home local generators, command to smart appliances, and task status will be provided to the applications as data-driven services. There are two main applications which use the data-driven services of smart home. The first one, which is a LabVIEW-based application, is used for querying on-demand readings from the AMI network, logging system's alarms, events or malfunctions. The second application which is the control unit collects all the required information from the energy server and sends optimal reference signals and set-points to related actuators and device-level controllers. This application also provides a supervisory control over the system performance and changes the plan of actions in different working conditions (e.g., normal or faulty) based on a predefined scheme.

IV. DISCUSSION AND CONCLUSION REMARKS

This paper proposed a new layered architecture for data processing and management of future smart homes. The proposed architecture could be deployed for any type of smart IoTs system including smart grid, smart retail, etc. As an example, the architecture was provided in more details for the case of a smart home. As discussed in the paper, future IoTs system needs to be ubiquitous and provides interoperability and shared data environment. In order to achieve these objectives in smart homes environment, a REST-based architecture was proposed for data processing and exchange of this platform. The architecture included seven main layers including; physical, fog-computing, network, cloud-computing, service, session and application layers. The concurrent research and development of these layers could help to provide an efficient strategy to deal with big data issues of future smart homes.

Compared to a conventional smart home which usually uses limited standalone storage and processing systems, the proposed architecture could use a scalable unlimited storage and processing system. Additionally, as the data-driven services have a standard data format with predefined APIs to access, a shared data environment could be provided by this architecture which is difficult to be addressed by the conventional smart home architecture.

To identify the required research and developments for the proposed smart home architecture, the studied platform was divided into lower and upper layers. The lower layers in the proposed architecture, include smart home physical, fog-computing, and network layers. These layers are the most mature layers of current smart homes. The main focus of research and development in these layers is on new sensing and communication technologies for different applications within smart home. There is extensive research work in this area during the last decades which aimed to develop cheap, efficient and accurate sensing and communication technologies for applications within smart home.

The upper layers of the proposed smart home architecture included cloud-computing, service, session and application layers. Authors believe that extensive research and development can be done in these layers. In the cloud-computing layer, although there are several studies on mathematical computing models for different smart home applications, standard computing pipelines should be developed for each application. Additionally, developing efficient data processing algorithms that use multiprocessing capability in the cloud can be another aspect for further research work in this layer.

In service layer, there is a need to define standard data attributes and format which can be used for smart home data views. Standardizing the format and attributes for these data views can help authenticated applications to efficiently exchange data with this layer. Based on the proposed REST architecture, data format such as XML, JSON could be a good option for this purpose.

In session layer, APIs and standard protocol should be clearly defined for data exchange and security. Both service and session layers need concurrent research work to provide a comprehensive shared data environment.

The last but not least, the smart home application layer includes all the applications which can exchange data with smart home service layers. Future studies can determine the opportunities of data-driven services which can be used by both smart home and smart city applications.

REFERENCES

[1] B. Hafidh, H. Al Osman, J. S. Arteaga-Falconi, H. Dong, and A. El Saddik, "SITE: The simple Internet of Things enabler for smart homes," *IEEE Access*, vol. 5, pp. 2034–2049, 2017.

[2] Z. Li, H. Shen, W. Ligon, and J. Denton, "An exploration of designing a hybrid scale-up/out Hadoop architecture based on performance measurements," *IEEE Trans. Parallel Distrib. Syst.*, vol. 28, no. 2, pp. 386–400, Feb. 2017.

[3] S. Chaudhuri and U. Dayal, "An overview of data warehousing and OLAP technology," *SIGMOD Rec.*, vol. 26, no. 1, pp. 65–74, Mar. 1997.

[4] K. Krishnan, "Data warehousing revisited," in *Data Warehousing Age Big Data*. Amsterdam, The Netherlands: Elsevier, 2013, pp. 127–145.

[5] K. Shvachko, H. Kuang, S. Radia, and R. Chansler, "The hadoop distributed file system," in *Proc. IEEE 26th Symp. Mass Storage Syst. Technol. (MSST)*, May 2010, pp. 1–10.

[6] R. Lutolf, "Smart Home concept and the integration of energy meters into a home based system," in *Proc. 7th Int. Conf. Metering App. Tariffs Electr. Supply*, Nov. 1992, pp. 277–278.

[7] H. Shareef, M. S. Ahmed, A. Mohamed, and E. Al Hassan, "Review on home energy management system considering demand responses, smart technologies, and intelligent controllers," *IEEE Access*, vol. 6, pp. 24498–24509, 2018.

[8] I.-Y. Joo and D.-H. Choi, "Distributed optimization framework for energy management of multiple smart homes with distributed energy resources," *IEEE Access*, vol. 5, pp. 15551–15560, 2017.

[9] V. Pilloni, A. Floris, A. Meloni, and L. Atzori, "Smart home energy management including renewable sources: A QoE-driven approach," *IEEE Trans. Smart Grid*, vol. 9, no. 3, pp. 2006–2018, May 2018.

[10] D. Costantino *et al.*, "Solving interoperability within the smart building: A real test-bed," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC)*, Kansas City, MO, USA, May 2018, pp. 1–6.

[11] R. K. Lomotey, J. Pry, S. Sriramoju, E. Kaku, and R. Deters, "Middleware framework for IoT services integration," in *Proc. IEEE Int. Conf. AI Mobile Services (AIMS)*, Honolulu, HI, USA, Jun. 2017, pp. 89–92.

[12] P.-Y. Ting, J.-L. Tsai, and T.-S. Wu, "Signcryption method suitable for low-power IoT devices in a wireless sensor network," *IEEE Syst. J.*, vol. 12, no. 3, pp. 2385–2394, Sep. 2018, doi: 10.1109/JSYST.2017.2730580.

[13] M. Tao, K. Ota, and M. Dong, "Ontology-based data semantic management and application in IoT- and cloud-enabled smart homes," *Future Gener. Comput. Syst.*, vol. 76, pp. 528–539, Nov. 2017.

[14] M. Tao, K. Ota, and M. Dong, "Foud: Integrating fog and cloud for 5G-enabled V2G networks," *IEEE Netw.*, vol. 31, no. 2, pp. 8–13, Mar./Apr. 2017.

[15] S. Jabbar, M. Khan, B. N. Silva, and K. J. Han, "A REST-based industrial Web of things' framework for smart warehousing," *J. Supercomput.*, vol. 74, no. 9, pp. 4419–4433, 2016.

[16] A. Iqbal *et al.*, "Interoperable Internet-of-Things platform for smart home system using Web-of-Objects and cloud," *Sustain. Cities Soc.*, vol. 38, pp. 636–646, Apr. 2018.

[17] S. S. Ara, Z. U. Shamszaman, and I. Chong, "Web-of-objects based user-centric semantic service composition methodology in the Internet of Things," *Int. J. Distrib. Sensor Netw.*, vol. 10, no. 5, 2014, Art. no. 482873, doi: 10.1155/2014/482873.

[18] A. Yassine, S. Singh, and A. Alamri, "Mining human activity patterns from smart home big data for health care applications," *IEEE Access*, vol. 5, pp. 13131–13141, 2017.

[19] G. Mokhtari, A. Anvari-Moghaddam, Q. Zhang, and M. Karunanithi, "Multi-residential activity labelling in smart homes with wearable tags using BLE technology," *Sensors*, vol. 18, no. 3, p. E908, 2018.

[20] M. Clarke, J. de Folter, V. Verma, and H. Gokalp, "Interoperable end-to-end remote patient monitoring platform based on IEEE 11073 PHD and ZigBee health care profile," *IEEE Trans. Biomed. Eng.*, vol. 65, no. 5, pp. 1014–1025, May 2018.

[21] G. Mokhtari, Q. Zhang, G. Nourbakhsh, S. Ball, and M. Karunanithi, "BLUESOUND: A new resident identification sensor—Using ultrasound array and BLE technology for smart home platform," *IEEE Sensors J.*, vol. 17, no. 5, pp. 1503–1512, Mar. 2017.

[22] A. Anvari-Moghaddam, H. Monsef, and A. Rahimi-Kian, "Optimal smart home energy management considering energy saving and a comfortable lifestyle," *IEEE Trans. Smart Grid*, vol. 6, no. 1, pp. 324–332, Jan. 2015.

[23] S. Kazmi, N. Javaid, M. J. Mughal, M. Akbar, S. H. Ahmed, and N. Alrajeh, "Towards optimization of metaheuristic algorithms for IoT enabled smart homes targeting balanced demand and supply of energy," *IEEE Access*, to be published, doi: 10.1109/ACCESS.2017.2763624.

[24] S. Moon and J.-W. Lee, "Multi-residential demand response scheduling with multi-class appliances in smart grid," *IEEE Trans. Smart Grid*, vol. 9, no. 4, pp. 2518–2528, Jul. 2018.

[25] A. Anvari-Moghaddam, H. Monsef, and A. Rahimi-Kian, "Cost-effective and comfort-aware residential energy management under different pricing schemes and weather conditions," *Energy Buildings*, vol. 86, pp. 782–793, Jan. 2015.

[26] S. Singh and A. Yassine, "Mining energy consumption behavior patterns for households in smart grid," *IEEE Trans. Emerg. Topics Comput.*, to be published, doi: 10.1109/TETC.2017.2692098.

[27] R. J. Robles, T. H. Kim, D. Cook, and S. Das, "A review on security in smart home development," *Int. J. Adv. Sci. Technol.*, vol. 15, pp. 13–22, Feb. 2010.

[28] K. Shahryari and A. Anvari-Moghaddam, "Demand side management using the Internet of energy based on fog and cloud computing," in *Proc. 10th IEEE Int. Conf. Internet Things*, Jun. 2017, pp. 1–6.

[29] P. A. Catherwood, D. Steele, M. Little, S. Mccomb, and J. Mclaughlin, "A community-based IoT personalized wireless healthcare solution trial," *IEEE J. Transl. Eng. Health Med.*, vol. 6, 2018, Art. no. 2800313.

[30] N. Marz and J. Warren, *Big Data: Principles and Best Practices of Scalable Realtime Data Systems*. 1st ed. Manning: Greenwich, CT, USA, 2015.

[31] A. Elmangoush, T. Magedanz, A. Blotny, and N. Blum, "Design of RESTful APIs for M2M services," in *Proc. 16th Int. Conf. Intell. Next Gener. Netw. (ICIN)*, Oct. 2012, pp. 50–56.

[32] M. Masse, *REST API Design Rulebook: Designing Consistent RESTful Web Service Interfaces*. Sebastopol, CA, USA: O'Reilly Media, 2011.

[33] E. J. Palacios-Garcia *et al.*, "Using smart meters data for energy management operations and power quality monitoring in a microgrid," in *Proc. IEEE 26th Int. Symp. Ind. Electron. (ISIE)*, Jun. 2017, pp. 1725–1731.

[34] A. Anvari-Moghaddam, J. M. Guerrero, J. C. Vasquez, H. Monsef, and A. Rahimi-Kian, "Efficient energy management for a grid-tied residential microgrid," *IET Gener., Transmiss. Distrib.*, vol. 11, no. 11, pp. 2752–2761, Aug. 2017.

GHASSEM MOKHTARI received the M.Sc. degree from the Amirkabir University of Technology, in 2011, and the Ph.D. degree from the Queensland University of Technology, in 2014.

In 2014, he joined The Australian e-Health Research Centre, as a Postdoctoral Research Fellow. He is currently with Deloitte consulting as the Manager specializing in emerging technologies, things, and big data solutions to create innovation that delivers economic and safety value to customers in Agile steps. His research interest includes the Internet of Things based solution for remote health monitoring. As a student, he received several awards, including the Faculty Top-Up Award and the Outstanding Research Student Award. He also serves as an Associate Editor for the IEEE ACCESS.

AMJAD ANVARI-MOGHADDAM (S'10–M'14–SM'17) received the Ph.D. degree (Hons.) in power systems engineering from the University of Tehran, in 2015. He is currently a Postdoctoral Fellow with the Department of Energy Technology, Aalborg University. His research interests include planning, design, control, and operation of energy systems, mostly renewable and hybrid power systems with appropriate market mechanisms. Dr. Anvari-Moghaddam is a member of Technical Committee (TC) of the IEEE IES Renewable Energy Systems and a TC Member of the IES Resilience and Security for Industrial Applications-ReSia, the IEEE Working Group P2004 (HIL Simulation Based Testing of Electric Power Apparatus and Controls), the CIGRE Working Groups on Rural Electrification (TOR C6.38), and the Distributed Energy Resources Aggregation Platforms for the Provision of Flexibility Services (TOR C6.35). He also serves as the Secretary of the IEEE Working Group on Smart Buildings, Loads and Customer Systems and a member of Technical Program/Advisory Committee for several international conferences. He was a recipient of the 2017 IEEE Outstanding Service Award (Exeter, U.K.) and the 2018 IEEE Outstanding Leadership Award (Halifax, NS, Canada). He is also the GE/Associate Editor of the *IET Renewable Power Generation*, IEEE ACCESS, IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS special issue: NEXT GENERATION INTELLIGENT MARITIME GRIDS, *Journal of Applied Sciences* special issues: *Advances in Integrated Energy Systems Design, Control and Optimization* and *Sustainable Energy Systems Planning, Integration and Management*, and *Future Generation Computer Systems* special issue: *Smart Data for Internet of Things*.

QING ZHANG received the B.Sc. degree from Tsinghua University, Beijing, China, and the Ph.D. degree in computer science from University of New South Wales, Sydney, Australia. He is currently a Senior Research Scientist and a Team Leader of the Health Internet of Things Team, The Australian e-Health Research Centre, CSIRO, where he leads the smart home and Internet-of-Things projects. His research interests include the variety of topics in sensor data fusion and mining, human identification, and activity recognition. He is a member of IEEE and a regular Reviewer of the *Journal of Medical Internet Research*, IEEE JOURNAL OF BIOMEDICAL AND HEALTH INFORMATICS, and so on. He received two Queensland State iAwards, in 2013 and 2014, and the National Merit Award, in 2013. He has served as the Vice-President of the IEEE QLD Section.