A Smart Home Energy Management System Using IoT and Big Data Analytics Approach

A.R. Al-Ali, Imran A. Zualkernan, Mohammed Rashid, Ragini Gupta, Mazin AliKarar

Abstract*—Increasing cost and demand of energy has led many organizations to find smart ways for monitoring, controlling and saving energy. A smart Energy Management System (EMS) can contribute towards cutting the costs while still meeting energy demand. The emerging technologies of Internet of Things (IoT) and Big Data can be utilized to better manage energy consumption in residential, commercial, and industrial sectors. This paper presents an Energy Management System (EMS) for smart homes. In this system, each home device is interfaced with a data acquisition module that is an IoT object with a unique IP address resulting in a large mesh wireless network of devices. The data acquisition System on Chip (SoC) module collects energy consumption data from each device of each smart home and transmits the data to a centralized server for further processing and analysis. This information from all residential areas accumulates in the utility's server as Big Data. The proposed EMS utilizes off-the-shelf Business Intelligence (BI) and Big Data analytics software packages to better manage energy consumption and to meet consumer demand. Since air conditioning contributes to 60% of electricity consumption in Arab Gulf countries, HVAC (Heating, Ventilation and Air Conditioning) Units have been taken as a case study to validate the proposed system. A prototype was built and tested in the lab to mimic small residential area HVAC systems[1].

***Index Terms*—Business Intelligence, Data Analytics, Energy Management System, HVAC, Internet of Things, MQTT, System on Chip.**

I. Introduction

Using energy efficiently in smart homes saves money, enhances sustainability and reduces carbon footprint at large. Consequently, the need for smart energy management is on the rise for smart homes and for smart cities in general. However, the lack of low cost, easy to deploy, and low maintenance technology has somewhat limited a large-scale deployment of such systems. The sheer quantity of data collected throughout different cities of a country presents multiple challenges in data storage, organization, and analysis. Internet of Things (IoT) technology and Big Data are natural candidates to address these challenges. IoT technologies can provide a ubiquitous computing platform to sense, monitor and control the household appliances energy consumption on a large scale. This data is collected using many different wireless sensors installed in residential units. Similarly, Big Data technology can be utilized to collect and analyze large amounts of data [1]. Data analytics on this data using business intelligence (BI) platform [2] plays an essential role in energy management decisions for homeowners and the utility alike. The data can be monitored, collected and analyzed using predictive analysis and advanced methods to actionable information in the form of reports, graphs and charts. Thus, this analyzed data in real-time can aid home owners, utilities and utility eco-systems providers to gain significant insights on energy consumption of smart homes. The energy service providers can use the power consumption data available with analytics engine to provide flexible and on-demand supply with appropriate energy marketing strategies. The consumers, being aware of their consumption behavior and having a close interaction with the electricity utilities, can adjust and optimize their power consumption and reduce their electricity bills. In order to have an effective cost saving system, it is important to monitor and control the operation of residential loads depending on the aggregate power consumption over desired period, the peak power consumption, the effect of weather/atmospheric conditions and consumption slab rates. This is where the combination of IoT technology, Big Data analytics and BI comes into play for implementing energy management solutions on a local and national scale. Finally, as an additional advantage, the use of IoT also enables seamless remote access control of home devices where the customers get online access to the ON/OFF usage pattern of in home appliances via a personal computer or a mobile phone.

Rest of the paper is organized as follows. Previous work in using Home Energy management System (HEMS) is presented next. This is followed by the proposed system requirements. The system architecture is presented next followed by a description of implementation details. Evaluation and testing is described and succeeded by the conclusion. Energy management in the context of smart homes spans the three areas namely; Smart devices, Wireless Sensor Networks (WSN), and Home Energy Management System (HEMS). A HEMS requires a reliable communication network

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using WSN that can transport the consumption details and consumer load behavior periodically. In [3, 4, 5], an implementation of a HEMS Unit in a Wireless Sensor Network using a ZigBee Module to communicate with sensor nodes, is presented. The system monitors the device consumption data and sends control signals to end nodes during peak load hours. However, the lifetime of a WSN network deteriorates with time due to the deployment of new sensors in the network. Additionally, Han et al. in [6] introduced a system for monitoring power consumption using ZigBee as the communication protocol in a WSN. However, in this system the data was collected and aggregated solely by the home server which could lead to data loss in case of a system failure. Moreover, a bridge between ZigBee and TCP/IP stack would be required to connect this system to a community of homes.

The above mentioned WSN networks have been extended to wider ranges in the IoT paradigm utilizing the GSM/GPRS networks to remotely control the end-devices in [7, 8]. Various studies have been steered in the application of IoT environment for HVAC control and scheduling methods to optimize HVAC energy consumption [9, 10, 11]. A hierarchical, smart-home service architecture employed with multiple in-home displays for user interfaces is described in [12]. In this research [12], a home controller system interfaced with device sensors is responsible for aggregated energy reporting of all devices to home owners. For community representatives, a community broker server is integrated with different home network devices such as security cameras within a community. Furthermore, a comparative analysis between Message Queuing Telemetry Transport Protocol (MQTT) and Hypertext Transfer Protocol (HTTP) is also performed to determine which protocol was more efficient in providing home control services [12]. The design of the proposed architecture, however, lacks the incorporation of Big Data which is instrumental in processing and analyzing huge volume of data collected from several home sensor networks.

Authors in [13] emphasize on IoT based DC powered homes to develop a DC distribution system encompassing all residential DC-based loads that interact with each other. However, the lack of standardized protocols and regulations were the main challenges in considering intelligent DC powered homes as suitable replacement to AC power systems. Challenges could be overcome with IoT that will provide an integrated platform for DC powered technologies in efficient energy distribution.

Multiple in-home display systems (IHDs) and automatic meter reading systems (AMR) were discussed in the context of providing energy management information in [14]. Depending on the ambient conditions, the smart home systems could choose the display devices such as TV, smartphone or tablet computers and accordingly select the appropriate user interface. The architecture, however, lacked a standardized user interface for all the home devices that could accomplish the requirement for multiple displays. A proposed architecture of HEMS utilizing power line communication was addressed in [15]. Using smart meter data, this HEMS can monitor and provide real-time information on home energy consumption along with online access to devices status, thus allowing remote control of devices by customers. The proposed design is based on standard HTTP protocol and does not provide support for lighter-weight communication protocol like MQTT which is essential to scale up the system in order to accommodate multiple residential areas. In [16], a residential gateway controller was developed with a central management system that generated an operation plan for all the connected nodes in a home network depending on weather conditions. The devices status and power consumption details were transported to the web server through an extensible markup language (XML) interface. Since XML files tend to be heavy weight for data delivery between browser and servers, the architecture will face significant bandwidth challenges in sending these large files across the network [16].

Additionally, the researchers in [17] propose a cost modelling scheme for an optimization based energy management model that aims at reducing energy expenses of consumers. Several scenarios such as local energy generation capacity, peak load hours of devices, length of cycle of each appliance, and time of use (TOU) tariffs have been taken into consideration for real time pricing of the application. In each case, the application was reported to reduce the energy expenses when compared to no energy management solution. EMS can be used to achieve a sustainable and significant reduction. Savings over 20% can be achieved on the long term using certified Energy Management Systems [18]. Another study found that Home energy management system can reduce electricity consumption by 16–19% potentially with acceptable discomfort [19]. Thus, home energy management system can be excellent add-on for home owners to reduce electricity consumption considerably while at the same time being more sustainable.

The literature review indicates that various communication protocols in a WSN have been utilized in EMS for smart homes. However, for a seamless integration of all residential devices, an open-source light weight communication protocol is required. This will foster interoperability leading to scalable systems. Installation of home EMS can help home owners to understand contribution of each device towards the overall electricity bill they receive. In addition, most previous work has primarily focused on individual smart homes and lack the energy management provisions for regional utility providers or national level utility centers. The technology to collect huge volumes of data from home sensor networks is available, however, managing the collected data efficiently and extracting deeper insights from it remains a challenge. The existing paradigms on EMS and cost saving models are implemented on discrete units while the proposed model can be built on top of the existing architectures to cater to a distributed EMS platform from consumer to community level stakeholders.

This paper presents the design and implementation of an EMS that addresses these shortcomings. The system proposed in this paper utilizes an IoT based communication protocol based on well-established standards like MQTT which makes the system scalable. In addition to this, the proposed system is empowered with analytics and Business Intelligence (BI) that provides a meaningful perspective on the collected data through dashboard visualization and reporting. Moreover, using Big Data based data storage technology ensures the system scalability on a national level, thus catering energy management services to both home owners as well as utility providers.

II. Proposed System Requirements

The functional requirements of the system are specified as general functional requirements and specific system requirements. The general requirements are the system's functionality and specific requirements are different business processes delivered. Non-functional requirements comprise of system's attributes such as scalability, security, privacy, etc.

The proposed system's functional requirements are:

- The SoC should gather power consumption information and the ambient condition information periodically, and send it to a centralized server.
- The server should parse the information and transmit the readings to a central data storage system or database.
- The stored data should be used by analytics engine to process it and generate reports, graphs, and charts.
- Clients should be able to view the generated graphs through a cross-platform mobile application.
- Client application interacts with the server using a lightweight architectural style Web API to facilitate communication using web services.
- Depending on the user privileges, the application should render different services to each user such as viewing reports, device status, and remote control of device or bill payment.

The specific functional requirements can be characterized as the business processes offered by the system. To render these requirements, six divisions of business processes are follows:

- Consumption Analysis for Monitoring
- Asset Efficiency Analysis
- Root Cause Analysis
- Predictive Analysis
- Remote and Local Device Controlling
- Bill Tracking Utility

The non-functional requirements of the system demonstrate that the system is scalable, reliable, secured, maintainable, easily deployed, and remotely accessible. Scalability, Security and Privacy are the three important non-functional aspects in the proposed systems which are discussed as follows:

A. *Scalability*

The data is collected and analyzed on a national level accommodating four different levels of stakeholders: Home Owner, Community Representative, State Representative and Country Representative. Each stakeholder has its respective view of the data and services offered. The six business processes mentioned above should be applied to each stakeholder as required. To serve these levels of clients, the system should be based on an easily scalable architecture.

B. *Security*

Security of the system is important as a minor flaw in system design can lead to catastrophic disasters. Multiple levels of security such as secured web service calls using https must be implemented to ensure protected communication of the system.

C. *Privacy*

The communication between server and end devices should be private. Access control using two factor authentication and proper encryption techniques should be utilized to prevent illegitimate users from prying over the data.

II. System Architecture

Based on the above system requirements, the proposed system's hardware and software architecture are as follows:

A. *Hardware Architecture*

As shown in Fig. 1, the hardware architecture of the system comprises of the following building blocks:

1) *Sensors and Actuators*

As the proposed system is to monitor and control the AC units, an integrated temperature and humidity sensor is interfaced with the microcontroller to measure the ambient conditions [20].

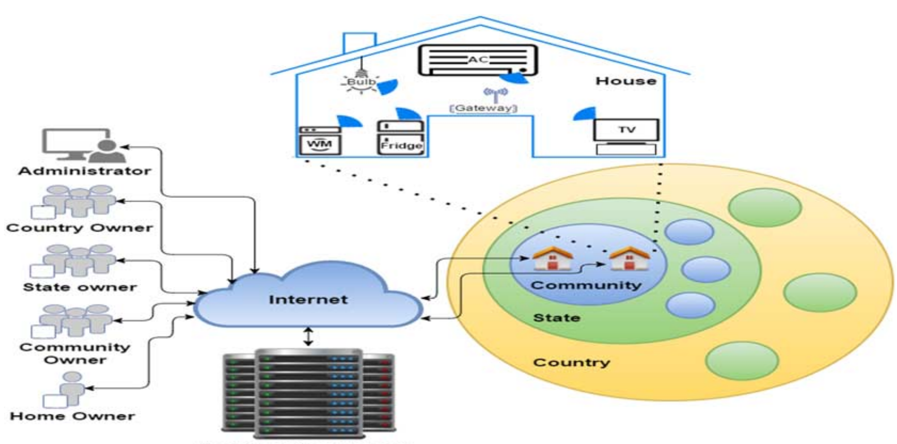

Fig. 1. System Architecture

In addition, a solid state relay is controlled by the micro-controller to switch ON/OFF the devices accordingly. A current sensor is used to measure the AC current to calculate the power consumption.

2) *High-end Microcontroller*

A SoC high end microcontroller is used as edge device data acquisition module that manages the HVAC unit [21]. The compact sized, high speed and lightweight SoC is suitable for residential areas. Table I displays the specifications of the micro-controller used in this study.

3) *Servers*

In the proposed architecture, the servers are high-end PCs which can also be deployed on Cloud for wide-scale accessibility. The installed servers are: MQTT Broker, highly scalable Storage Server, Analytics Engine server, and a Web server. The functionality of each server developed and utilized will be explained in the software architecture section.

TABLE I
MICRO-CONTROLLER SPECIFICATION

Component	Description
Digital Ports	18 I/O ports
Analog Ports	8 ADC and 2 DAC
Memory	1MB Flash, 128 kB RAM

B. *Software Architecture*

Software architecture consists of three primary building modules; data acquisition module on the edge device, middleware module, and client application module:

1) *Data Acquisition Module*

The data acquisition module has two functions namely, monitoring function and controlling function. The monitoring function continuously reads the ambient temperature, humidity and the AC power consumption transmits the readings to the middleware module through MQTT protocol. These parameters are framed and reported to the middleware periodically in standard MQTT format. For example, the data frame has the user ID, house ID, device ID and the sensor values. The control function is used to receive the commands from the middleware module to turn ON/OFF the AC-Units accordingly.

2) *Middleware Module*

Middleware module consists of several software tools and servers that provide different services as explained below:

i. *MQTT Server*

MQTT server (Broker) [11], provides a medium for the communication between the edge device (home appliances such as AC-Unit) and the middleware. On the broker side access control was enforced to prevent unauthorized access to certain topics. Some topics such as consumption reporting topic and device state change reporting topic is configured as write only. Only those with required privilege can read what is being published. Topics like control command is configured as read only, so that unauthorized controlling of device is prevented.

ii. *Storage Server*

A highly scalable storage server is used as data warehouse for storing the edge devices' sensor data and user information [1]. It can handle the generated Big Data from residential units as well as scale up to more residential areas that can be added in future. A high performance and scalable database is required to store information related to users, user-house relations and house-device relations. Operational database that runs on top of existing scalable storage server was chosen [23].

iii. *Analytics Engine server*

An off-the-shelf business intelligence software tool was utilized to make smart decisions from the received big data [2]. For example: the measured data is sorted and classified based on temperature, humidity and power consumption per house. This classification is used to generate reports, graphs, and charts that identify the consumption pattern of the houses in a residential area. This enables every house owner to see his/her own power consumption pattern based on the ambient conditions. Moreover, benchmarking feature allows users to compare their consumption details with those with similar setups.

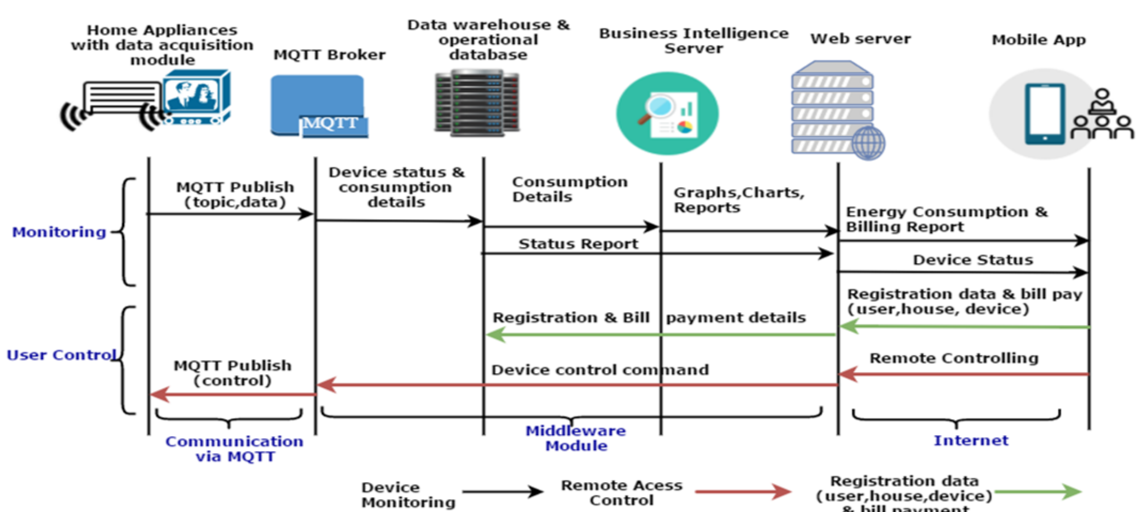

Fig. 2. Sequence Diagram

Accordingly, home owner can turn ON/OFF the device based on such information if needed. In addition to that, the tool can empower local utility and regional utility to see the energy consumption pattern according to their respective privileges. For example: a local residential utility center can view each individual houses' aggregate consumption within its geographical area. A state utility center can view the aggregated consumption of each residential area in the state. The centralized Utility center can view each state's consumption pattern. These reports and graphs will be rendered to the client application through the web server.

iv. *Webserver*

The client application accesses the operational database through different web services implemented using JavaScript [24]. These services are used to transmit data to and from the database and send it back to the requester. Web services are used by the client application to authenticate monitor and control devices, view registered properties, and view registered devices, monthly bill viewing/paying and viewing graphs appropriate to the level of the user. HTTPS protocol is used to design web services to encrypt the traffic flow.

3) *Client Application Module*

A cross-platform IDE was used to develop the front end mobile user interface [25]. The advantage of using such an environment is that it utilizes standard web development languages. It also ensures the cross-platform feature for application which means that only one application is developed for different mobile phone platforms without the need for reimplementation. The application uses two types of authentication; the regular username-password combination is used to initiate connection. Once the user is authenticated a random generated string called API key is used to authenticate operations. This key can be changed anytime, API key changes per session. Once the user logs out, the API key is changed. Moreover, to make granting privilege like making a user a state-owner requires an additional parameter called secret key is used. This key changes daily, weekly or monthly and is only to be known by the top-level employees. Fig. 2 displays the overall sequence diagram showing the two-way data flow from home devices to end user application; one way is for monitoring device consumption details and other is for remote access control by the end user.

III. Implementation

To validate the architecture of the proposed system, a prototype was designed, built and tested in the lab. The prototype architecture consists of various hardware and software modules. In this section the hardware and software components used in the system prototype are described in details as follows:

A. *Hardware*

The hardware consists of a sensor array, high-end microcontroller, and relay banks. The sensor array comprises of RFID reader, temperature, humidity and current sensors. These sensors collect the device status and report it to the microcontroller periodically. The RFID module consists of RFID tag and a reader for each home device which is used for the local control of the device by swiping the tag through the reader by the home owner [26]. As mentioned in the previous section, the microcontroller [21] is a high end single SoC on the edge that collects the information from the sensors and forwards it to the servers for further processing via MQTT broker. Since the microcontroller cannot provide enough power, a solid state relays bank was used to provide a power driving circuit for the appliances. For the implementation in lab, 220 volts AC fans are used to mimic HVAC units. Depending on the different business processes, the microcontroller can be programmed to function differently for each scenario. For consumption analysis, the microcontroller is programmed to collect the temperature, humidity and power consumption data from the sensors. The data is framed in a lightweight format [27] compatible with MQTT server. This framed data is attached with the user, house and device details as shown in Fig. 3. To implement remote controlling of devices through client application, the microcontroller reports the status of the device whenever the state of device is changed. To enable the billing utility process, the microcontroller transmits the total power consumption of the device every day to the servers via the MQTT protocol. Fig. 4 shows the prototype that was built in the lab to mimic the proposed system.

User ID	House ID	Device ID	Power (kwH)
Humidity (%)	Temperature (C)	MQTT QoS	Message ID

Fig. 3. Data Frame-Payload

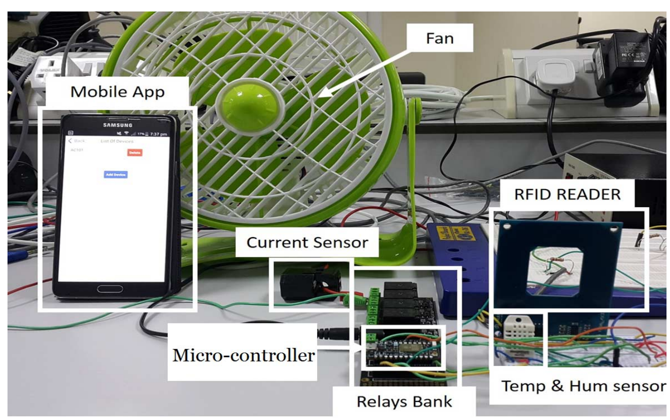

Fig. 4. Hardware Components

B. *Software*

The software implementation involves benchmarking and data analysis techniques using Business Intelligence tool to generate graphs, charts and reports in real time. This was followed with the development of a mobile application to render the generated graphs, charts, and reports to end users. A description of these software modules is given as follows:

1) *Benchmarking and data analysis using BI platform*

One of the primary analysis techniques in data mining is benchmarking. Benchmarking the data sets can help identify which houses or residential areas should be focused on for setting optimal energy management goals and policies. The business intelligence software tool serves as an optimum platform for benchmarking real time data and generating user-interactive charts and reports [2]. Different benchmarking scenarios are deemed for the four stakeholder levels as mentioned in the previous section. For example, a stakeholder like home owner in a residential area is entitled to view the graphs and charts for the total power consumption of his/her house on a daily, monthly, and annual basis. The user is prompted to enter his/her house ID and select the year for which he/she desires to view the power consumption of each device in the house as shown in Fig. 5. The home owners can use benchmarking service to compare their power consumption with other housing units that have a similar setup. For community stakeholders, they are entitled to monitor power consumption of all houses in their respective community. There are two types of settings involved; first, benchmarking annual power consumption of each house against per square feet power consumption. Second, categorizing each house depending on its annual power consumption with respect to the house-age. The community owner is prompted to enter his/her respective community ID in order to obtain the desired graph or chart. A screenshot of annual power consumption chart for several housing units with their respective house IDs in a community is shown in Fig. 6. It's worth mentioning that the same chart can be obtained on a daily or monthly basis. The state stakeholders at a state utility center can view data set distribution across regional communities within the state. Also, they can view the average power consumption spread across different communities on a monthly and yearly basis. The graphical data will be used to create benchmarks based on past records for conducting root cause analysis which is one of the business processes as mentioned previously. The trend line graphs can help predict the nature of power consumption of the state with respect to weather conditions (temperature) in future as shown in Fig.7. The Country stakeholders at a Centralized Utility Center are the highest level authority in the stakeholder hierarchy. These owners can view annual power consumption of each state in a country. The aggregated energy consumption can be compared to the overall energy generation from the central power generation station. This can assist the state to plan and implement data driven energy strategies and decisions. Additionally, the country owners can check online the temperature, humidity and power consumption variation across different states using the Geo-Map service. They can inspect power consumption of states based on consumption slab rates using an Energy map as shown in Fig. 8.

2) *Client Application*

A cross-platform application is developed that gives access to every stakeholder a different view to the data analytics according to his/her privileges. Once a user logs in, a service will run to get the user privileges and the user interface components that he/she will be able to see consequently. For example, for the home owner, there are two services available; first is monitoring power consumption data of each house device as shown in Fig. 6 and second is remote control services (ON/OFF) for house devices as shown in Fig. 9(a). For the bill tracking service, the user can view the monthly bill and pay the due amount online as shown in Fig. 9(b).

IV. Evaluation and Testing

A set of criteria were developed to evaluate system performance for scalability, speed and security. Scalability is the main concern for the MQTT Server and Web server to accommodate all customers on national level. Speed was also important for querying to and from the storage server or operational database. It's worth mentioning that the security aspect of the proposed system is under development.

A. *MQTT Server Scalability*

A network analysis tool was used to measure the following metric: Throughput, Latency, and Packets dropped [28]. For an experimental comparison, a logarithmic scale of clients was chosen to send 1, 10, 100, and 1000 consecutive messages with a reliability of Quality of Service: QoS-0 and QoS-1 in each case. QoS-2 was excluded in test cases due to its large overhead. Table II represents different test case scenarios indicating that the system was able to accept 1000 concurrent MQTT clients publishing messages to a subscribed topic of the MQTT server. From the results as shown in Table II, it is evident that the overall latency for QoS-0 is always lower than that for QoS-1 irrespective of the number of concurrent client requests (See Fig. 13). This difference is expected because in QoS-0 message delivery is not acknowledged whereas in QoS-1 acknowledgment for confirmed message reception is sent, which adds to the latency of message transmission in QoS-1. Also, the throughput for QoS-1 was observed to be higher than that for QoS-0 for any number of clients since QoS-1 offers a reliable means of communication due to message acknowledgement and persistent session (Fig. 10). However, packet loss for QoS-1 was reported to be higher than that for QoS-0 in case of 1000 and 10000 clients. This is because in QoS-1 message acknowledgement and duplicates led to too much traffic in the network causing the network to drop more number of packets during transmission as opposed to QoS-0. Taking these results into consideration, the team chose to use QoS-0 for sending sensor readings from the edge appliance to the MQTT server because these readings are required to be reported constantly in very short intervals irrespective of one or more messages loss. Whereas QoS-1 reliability was utilized for passing commands to change the state of the device remotely via the client application. This ensures that message is received by the device.

B. *Scalability for Webserver*

Many users were simulated concurrently using a Webserver Stress Tool. Each user in this test makes a request involving operational database. CPU and Network utilization were high when all requests started coming as shown in Fig. 12. Almost all requests were answered immediately up to 4000 users. Beyond 4000 users the communication was terminated due to data traffic congestion and testing tool limitation. Memory

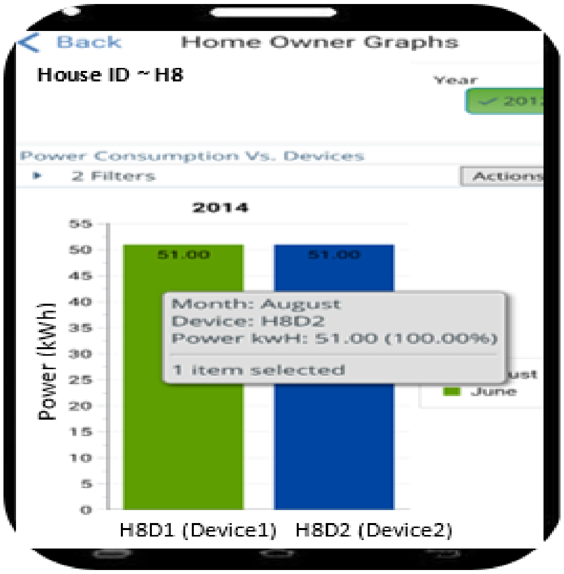

Fig. 5. Home Owner View-Monthly power consumption (kWh) for each device in house- H3

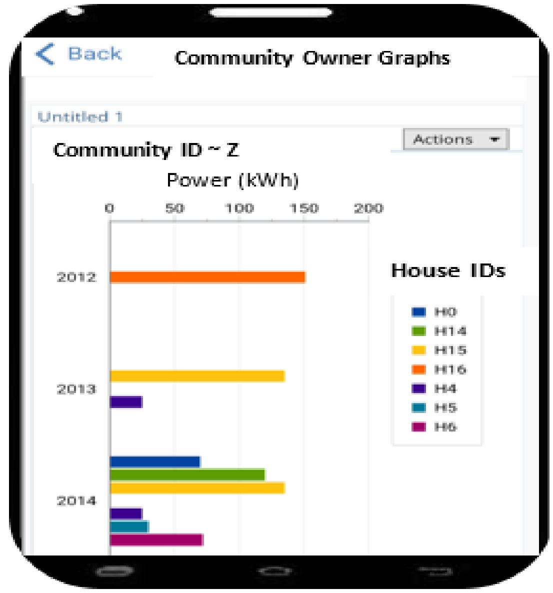

Fig. 6. Community Owner View-Annual power consumption (kWh) of each house in Community-Z

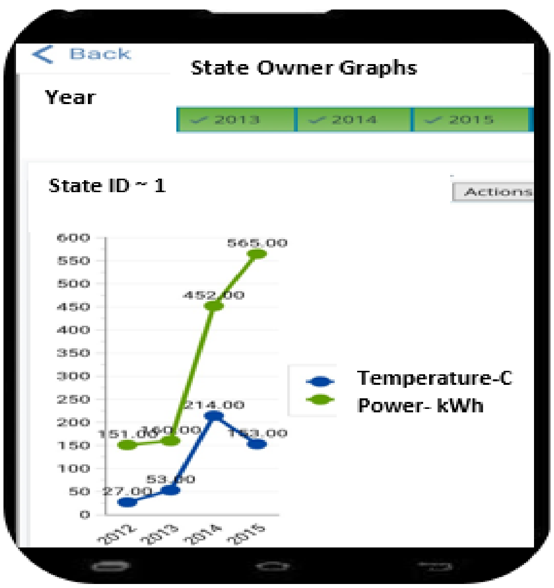

Fig. 7. State Owner View-Relationship between annual power consumption (kWh) and temperature (C) spread

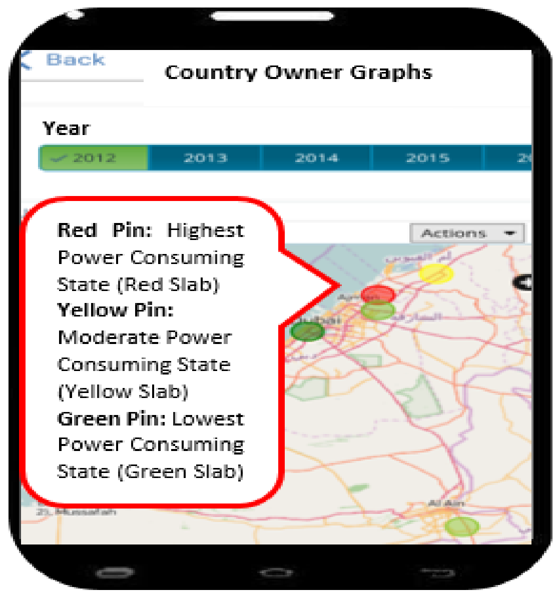

Fig. 8. Country Owner View-Energy Map with all states and their annual power distribution slab-wise

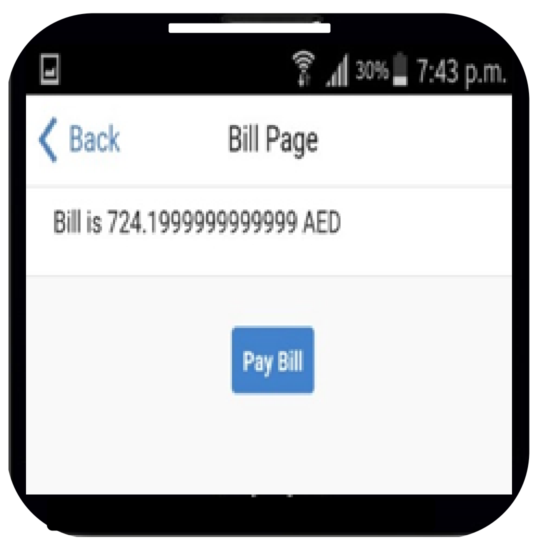

Fig. 9. (a) Remote control of devices (b) Monthly bill management

remained about 85% throughout the test. This is due to database read and writes activity that runs asynchronously in the background.

C. *Speed for Storage Server*

The data server speed was acceptable up to 4000 concurrent users. This is again due to the data traffic congestion and testing tool limitation. The time lapse for querying up to 4000 concurrent requests involved storage server operations. Read operation was performed by the storage server using web services. Moreover, an ETL (Extract-Transform-Load) script was written to measure the time taken to read from storage server during peak time. 4000 files, each 62 Bytes in size, were extracted from the storage server for read operation. A summary of the response time to complete read and write operation by the storage server is shown in Table III.

TABLE II
MQTT TEST CASES AND RESULTS

Number of Clients	Throughput (kbps)		Latency (ms)		Packets Dropped (%)	
	QoS-0	QoS-1	QoS-0	QoS-1	QoS-0	QoS-1
1	2.0	2.6	37	38	0	0
10	3.6	3.9	66	78	0	0
100	3.5	4.9	70	74	0	0
1000	105.5	57.9	92	112	2.9	2.6
10000	124.3	101.5	126	135	3.1	3.8

TABLE III
STORAGE SERVER READ AND WRITE
PERFORMANCE FOR 4000 CONCURRENT REQUESTS

Maximum response time	122.382	4.062
Average response time	065.925	3.771
Minimum response time	000.329	3.481

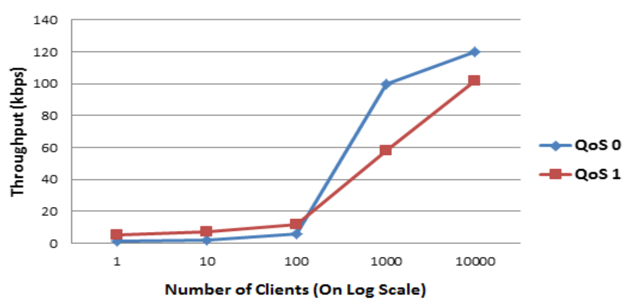

Fig. 10. Throughput (kbps) Vs. Number of clients' graph

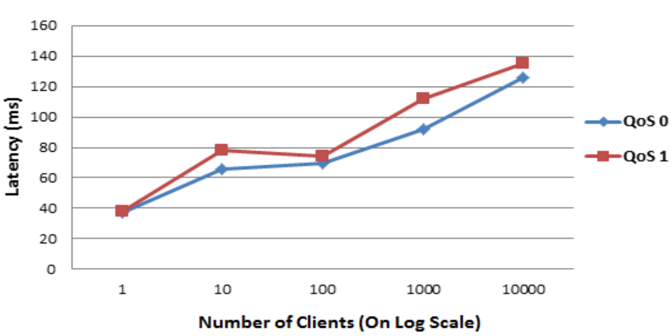

Fig. 11. Latency (ms) Vs. Number of clients' graph

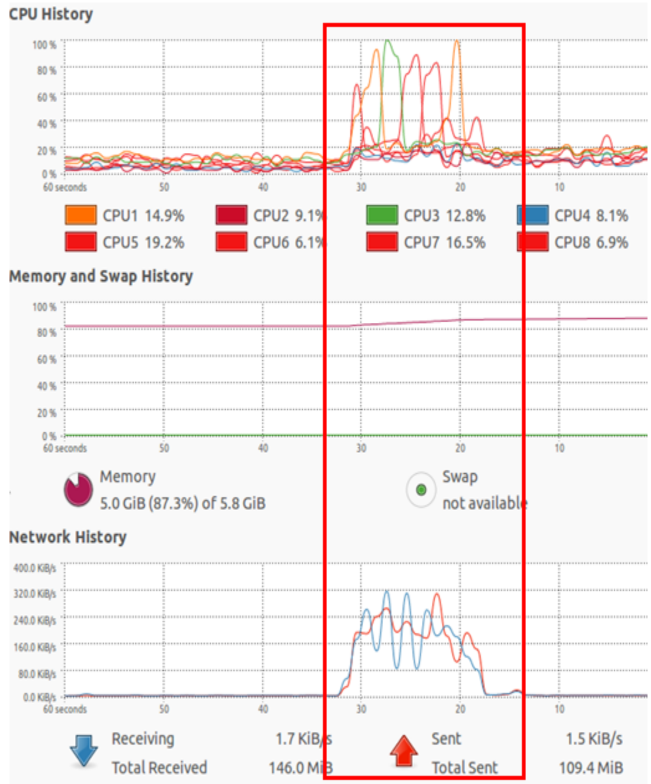

Fig. 12. Server performance during request phase

V. CONCLUSION

The proposed work is set to open new avenues for smart energy management on IoT and Big Data platform. The system design uses data analytics and scalable storage for building a smart EMS to aid different stakeholders with their respective privileges. The system empowers users to remotely monitor and control devices, and online bill generation via a friendly user interface mobile application

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