Development of an IoT-Based Electrical Consumption Measurement and Analysis System for Smart Homes and Buildings

Héctor F. Chinchero
Electric Eng. Dep.
Pontificia Universidad Católica del Euador PUCE
Esmeraldas, Ecuador
hfchinchero@pucese.edu.ec

J. Marcos Alonso
Electric Eng. Dep.
University of Oviedo
Gijón, Spain
marcos@uniovi.es

***Abstract*—This work analyses technological methods, elements, and tools for measuring electricity consumption in homes and buildings. The study focuses primarily on Automatic Meter Reading (AMR) to determine the consumption of lighting systems, HVAC devices, telecommunication systems, and appliances for homes, offices and working environments. An electrical consumption measurement and analysis system is introduced using consumption measurement nodes integrated into a metering network implemented over an Internet of Things (IoT) infrastructure with TCP/IP WiFi protocol. Energy management is performed using open, interoperable multiplatform technologies for monitoring employing user interface devices such as smartphones, tablets, and computers with Operating System (OS) from different manufacturers that enable to deploy AMR services with cloud integration.**

***Keywords*— Automatic Meter Reading (AMR), Internet of Things (IoT), Energy Management System (EMS), Smart Meter Node (SMN).**

I. Introduction

The energy consumed in homes and buildings is mainly related to the human activities carried out in the environment, the climatic conditions of the geographical region and the available technologies of consumption and optimization of energy efficiency. While developed countries generate more than 50% of Green House Gases (GHG) [1], they also implement more efficient policies and technologies than developing countries. On the other hand, policies, regulatory framework, and energy efficiency culture play a key role in this scenario to dramatically reduce the environmental effects caused by an irrational use of energy. There is now a strong drive to deploy increasingly efficient, as well as energy-optimized devices, technologies, and solutions [2]. All of these efforts have also now focused on meeting sustainable development goals, which to some extent contribute to recommendations, standards, protocols, and regulations to ensure healthy, safe, and sustainable environments [2].

It is estimated that the electricity consumed in homes and residential buildings is approximately 30% of all energy produced [2][3]. This energy is mainly associated with lighting systems, HVAC systems, appliances and electrical infrastructures of Information Technologies (IT), such as security, telecommunications, home automation systems among others. This distribution of consumption by systems in the environment must be analyzed independently and according to the human activity [3][4]. However, a technical estimate of the importance of each of these systems may be made when looking for energy efficiency optimization methodologies for consumption in these environments.

To achieve energy efficiency objectives in environments it is necessary to measure consumption, so the reading of electricity consumption is mainly done using Automatic Meter Reading (AMR) systems [3]. AMR is a technological concept that allows the users to automatically collect consumption data, perform a diagnosis and check the status of devices such as water, gas, and electricity meters [3][5]-[7]. The information of the AMR system is transferred to a central database that is used for analysis, troubleshooting, billing, and other applications [3]. On the other hand, AMR is implemented using integrated electronic meter devices with communications technologies based on wireless and wired technology platforms, radio frequency (RF) or power line carried communication (PLCC) [3]. Currently the Internet of Things (IoT), allows the designers to integrate consumer measurement devices into communications networks for the development of Energy Management Systems (EMS) in smart cities applications or individual management of home energy from anywhere in the world [7]-[9].

Energy Management System (EMS) is a concept oriented to the optimization of energy consumption, which is based on energy efficiency protocols and standards such as ISO50001:2018, Green House Gas (GHG) Protocol, LEED, BREAM, etc [4]. The goal is to implement methodologies to ensure efficiency criteria through systems such as the Energy Building Management System (EBMS) and Energy Home Management System (EHMS), among others [3][4]. Utility companies, such as power companies, increasingly require the development of Remote Telemetry Systems (RTS) for energy meters in corporate buildings, industry, stadiums, education campus, street lighting networks, special customers, residential buildings, etc. [3]. Utilities use RTS to perform the most appropriate monitoring, management and billing of energy meters installed on end consumers.

This work presents the development of a system for measurement and analysis of electricity consumption in Buildings and Homes based on IoT devices for the implementation of Telemetry Systems for energy meters in residential customers and office buildings.

II. Technologies and Systems for AMR

A. Automatic Meter Reading AMR

Different methods are used for measurement of electrical consumption. Among the most conventional techniques are the clamp meter, digital wattmeter, and digital electric meter. Other systems are also used to digitalize consumption information in pulses such as the KAMSPTRUP 382 model, to integrate them for example into meter network devices with M-BUS, RS485, LonWorks, BACNet, KNX protocols, etc. [4]. Currently AMR technologies can be integrated with EMS in buildings, such as those achieved using MeterBUS measuring devices with BUSing protocol [10] or SONOFF

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type electrical appliance meters with TCP/IP protocol using WiFi wireless communication [11].

AMR was first tested in experiments conducted by AT&T company in collaboration with Westinghouse Electric company. AT&T offered AMR services based on cellular systems at a reduced Price. The year 1985 is seen as the beginning of the modern era for AMR when several large-scale impact projects were implemented. Equitable Gas Go LLC and Hackensack Water Co companies were the pioneers on a large scale in the implementation of AMR for water and gas meters [4].

On the other hand, the advances made in the field of IoT, allow developers to design AMR devices based on processors from manufacturers such as AMD, Microchip, Cypress Semiconductor, Arduino, and others. The ease of integration of processors and development boards allows designers to even implement communications of devices developed with wired communication from RS232, RS485 and Ethernet, to wireless communications using RF protocols such as ZigBee, WiFi, Bluetooth, LoRa, LoRaWAN, GSM/GPRS/LTE, etc. [5][12]. This makes it increasingly easy to develop more complex systems where services such as those proposed in this study are established, at a reasonable cost and easy to implement. Figure 1 shows a scheme of the elements that make up an AMR System.

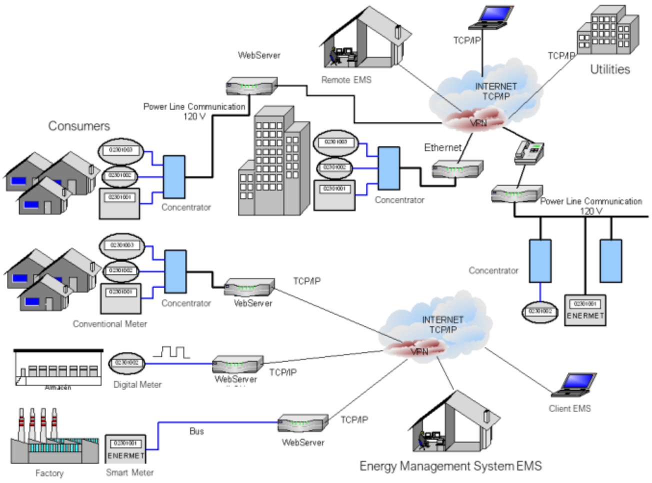


Fig. 1. AMR System Scheme.

B. *Main Components of an AMR System*

Meter Interface Module: The electrical meter consists of the power supply, the meter's own sensors, control electronics, and a communication interface that provides the possibility for the measured information to be transmitted from the remote AMR device to any central location for energy management [3]. Communication is usually bidirectional and can accept orders from a management console to also be received remotely by the meter. It is also necessary that any meter, such as water, gas or electric has built-in this interface unit so that it can be read remotely.

Communication System: It is the telemetry system, also called Supervisory Control and Data Acquisition (SCADA) System used for data transmission and control of signals generated between meter interface units and the central management office [3]. These systems are generally implemented using radio frequency (RF) communications, DialUp wired telephony, PLCC (Power Line Carrier Communication), GSM/GPRS/LTE last mile communications [3], or using new Machine to Machine (M2M) technologies such as LoRa, LoRaWAN, SigFox, Wimax, Optical Fiber (OF), among others [3][4][12].

Management System: This system includes computers and energy management tools, controller nodes, communications nodes, information concentrators with web server services, host links, switches, routers, GSM/GPRS/LTE or M2M receiving modems, etc. [3]. Energy Management is also known as EMS (Energy Management System) and is responsible for implementing management strategies such as those established in ISO50001:2018 standard to implement energy efficiency criteria, near-zero energy building (nZEB) methodologies, GHG protocol recommendations, etc. [3][4]. In addition, Open and Interoperable technologies are used for the development of applications and management tools. The most relevant tools are OpenLNS in Lonworks technology [13], ETSPro for KNX protocols [14], SIDE in BUSing technology [10], JavaScript, JASON, VisualStudio, among other integration tools with MySQL Database (DB), MariaDB, etc., using Operative Systems (OS) such as WindowsServer, iOS, Android aSC, Linux, etc. [10]-[15].

C. *Comparison between Energy Meters for AMR Systems*

Table 1 shows a comparison between AMR Energy Meters considering the technology evolution in order to analyze possibilities of integration. As can be seen POWR2 SONOFF, PM350, KAMSTRUP382 and MeterBUS have the best performance for integration with network protocol communication in a IoT infrastructure.

Table 1. *Comparison between AMR Energy Meters*

Parameter	Digital Meters	M.BUS Ingen.	382 Kams.	Pm350 Cet	Powr2 Sonoff
Wireless		X		X	X
Smart Meter		X	X	X	X
Real Time	Local	X	X	X	X
OS Compat.		All	All	All	All
Network Protocol		BUSing KNX	MBUS TCP-IP	TCP-IP	TCP-IP
IoT / WiFi		Wings WiFi		LoRa WAN	WiFi
Remote Control	Local	X	X	X	X
Consumption Report		X	X	X	X
Reprogram.	Factory	X	Factory	X	X
Energy Management	X	X	50001:2018	X	X
Low Cost	X	Medium	High	High	X

III. ENERGY METER SYSTEM USING IOT

The proposed system includes electrical energy consumption meter nodes with WiFi communications to implement an IoT network for an AMR system for residential environments or residential buildings. A concentrator node is specified based on a Raspberry Pi Web Server module that allows the users to concentrate information from IoT energy consumption meter nodes. This allows the system to include real-time device monitoring applications for the deployment of energy management services in homes and buildings. Figure 2 shows the scheme of the proposed AMR system.

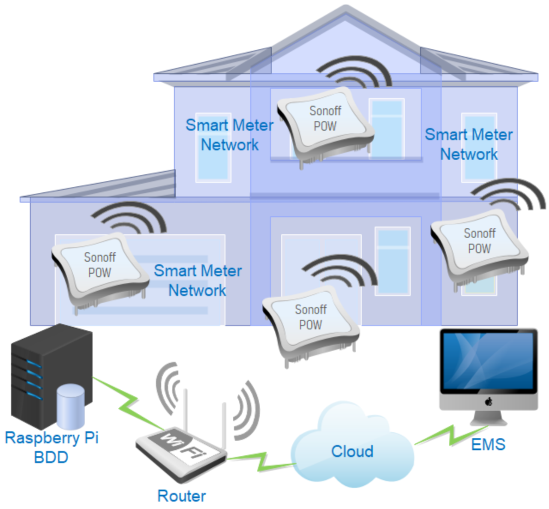
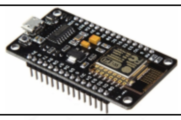
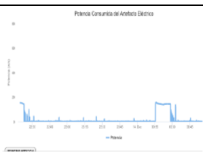


Fig. 2. Energy Meter System Using IoT.

A. *Technical Specifications for Energy Meter System Using IoT Smart Nodes*

Table 2 shows the technical specifications of the principal devices that are used in an AMR System using IoT Smart Nodes. As can be seen, the infrastructure includes Sonoff POW 1,2,3 version Smart Meter Node for analysis and measure the energy consumption in devices such as electrical iron. On other hand the IoT Smart Node has the MCU ESP8266 embedded, this device is used to test network communications. In addition, a Raspberry Pi Web Server is used for implement the EMS software using a Graphical Management Interface (GMI) for power and energy monitoring of IoT Smart Nodes implemented in the AMR System.

Table 2. *Minimum Technical Components Specifications*

Reference Device	Function	Device Image
Sonoff POW 1,2,3	-Power Meter 1 Channel -Wifi 802.11 a/b/g/n - Support loads up to 16 A - Firmware Open Source -Residential Applications	
Web Server Concentrator Node (Raspberry Pi)	-Web Server with Maria DB -Raspbian OS -Integration Open-Source Programming Languages -WiFi Communication. -RJ45, USB; I/O Ports	
IoT MCU Node	-IoT Node -WiFi 802.11 a/b/g/n. - ESP8266 embedded. - Serial and I/O Ports	
Data Base	Data Storage Open Source MySQL, MS SQL Server, Oracle, Maria DB, etc.	
Integration Tools	Open Source: Visual Basic, Java Script, Python, Cloud Services Integration. Network Integration Management Apps Design	
Management Client Interface	Graphical Monitoring Energy Management Energy Web Services Communication Settings IoT Node Interface Real Time PC, Smart Client Devices	

B. *Energy Reading Algorithm Using IoT Nodes*

The reading of energy consumptions on each IoT Node is performed according to the flowchart of the algorithm shown in Figure 3.

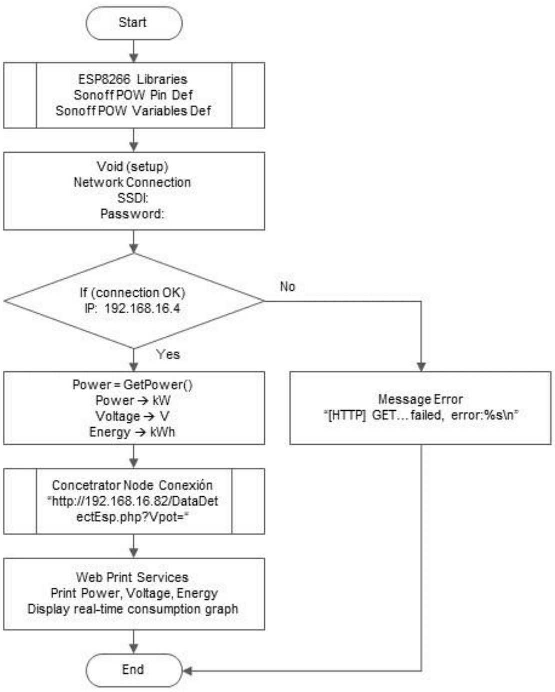


Fig. 3. IoT Node Algorithm Flowchart.

The following describes the process implemented by ESP8266 MCU or Sonoff Pow device.

Connection to TCP/IP network: This process makes a connection to the network using SSDI and user key. If the network connection is successful, that is, if communications are established on the home WiFi network using the IP address assigned to the IoT node, then the operation passes to the next point to get the consumption data. Otherwise, the named failure event (HTTP) GETFailed, error occurs; the algorithm finishes and the whole process restarts.

Get Consumption Values: To get power consumption, the GetPower() function is implemented and the value is assigned to the Power floating-point variable.

Calculation of Parameters: At this point a unit conversion of the loaded value is performed in the Power variable. The obtained value is transformed using GetPower() function, which is in Watts [W] to kilowatts [kW]. Then a transformation of the consumption obtained from the time is made to have it defined in kilowatt hour [kWh].

Connection to Web Server Concentrator Node: Once the consumption information has been obtained and transformation of units is done, communications are established with the Web Server Concentrator Node to send the information. The next routine is used to connect to the Raspberry Server IP address: "http://192.168.16.82/DataDetectEsp.php?Vpot=".

Once the communication is established, variables are sent to the Raspberry Pi Server for printing on the Web Interface for users.

C. *Energy Management Service*

AMR IoT System Energy Management is done by accessing the web server services running on the Raspberry Pi 3 implemented. The management algorithm responds to the flowchart shown in Figure 4.

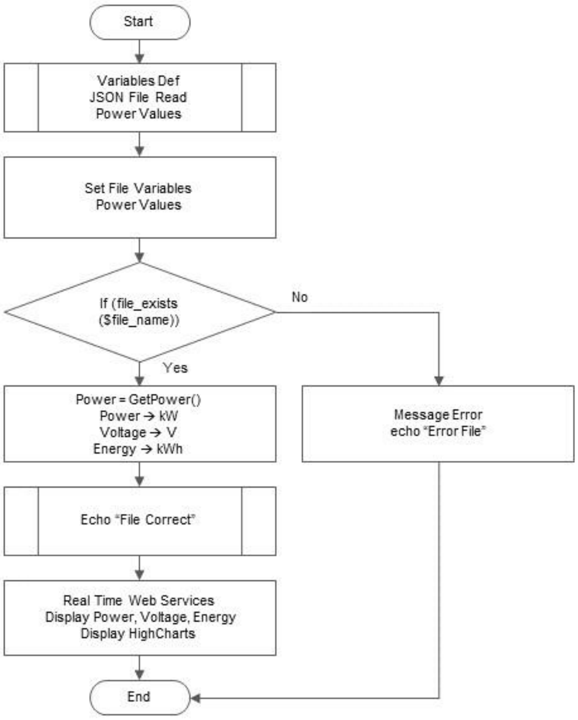


Fig. 4. Energy Management Service Flowchart.

This algorithm corresponds to the data reading part and allows to graph in real time using the values obtained of power depending on the time. If everything is correct, a line diagram is displayed using the Charts tool in which it is possible to display all the obtained values of any electrical device that has been connected to each IoT Node Meter. If the comparison is negative, an error message is displayed. The final user interface presents all the values obtained by each of the consumption metering nodes, such as power, voltage, and consumption, respectively. In addition, this interface displays the real-time consumption graph of each IoT Smart Meter Node (SMN) implemented in the AMR System, as shown in Figure 5.

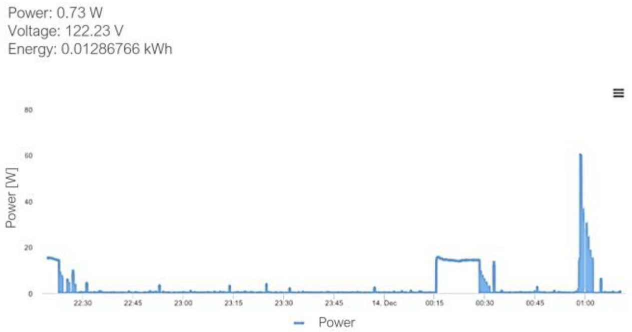


Fig. 5. Energy Management Web Interface for IoT Smart Meter Node.

IV. Implemented Prototype

A. *Implemented Prototype and Functionality Test*

Figure 6 shows the prototype of the deployed AMR system, which includes the IoT Smart Meter Node, the Concentrator Node, and communication elements for the WiFi network used for the IoT node network integration.

Fig. 6. AMR System Implemented Prototype.

For operational testing, tests are performed using different household appliances in the residential environment to measure data corresponding to the electrical power consumed from each of the devices and the maximum load that is supported by the prototype IoT Smart Meter Node.

B. *Test1: MCU ESP 8266 with random data.*

The MCU ESP 8266 device and the Raspberry Pi are used to verify communication between the IoT SMN and the Concentrator Node Web Server. Initially the data sent by MCU ESP8266 are random in a range of 10 to 230 Watts of power as shown in Figure 7. As can be seen, the Web Interface displays the Power, Voltage and Energy Consumption in real time. The Chart shows the consumption behavior during a time in which the information of power is stored in the Raspberry Pi based Concentrator Node.

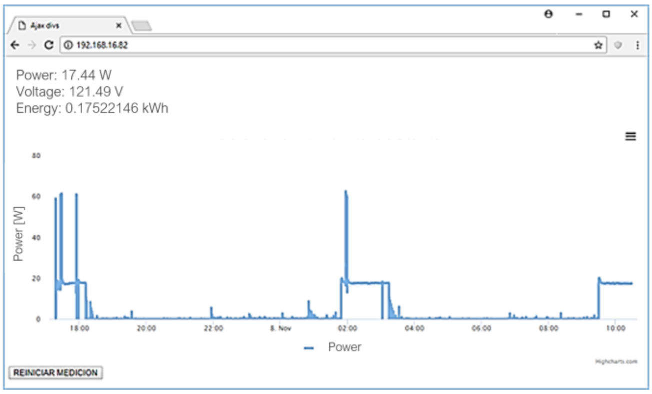


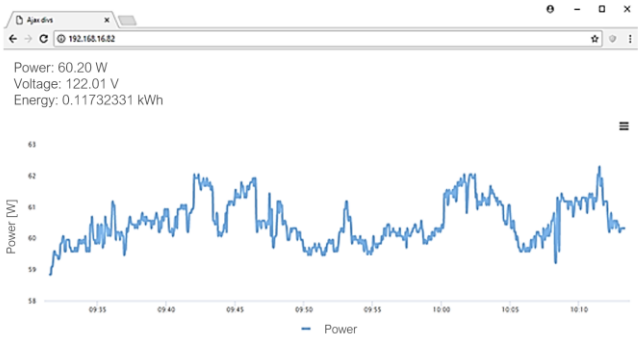
Fig. 7. Power Monitoring Interface: Communication Test using IoT Nodes with random data.

C. *Test2: Implemented Prototype using residential loads.*

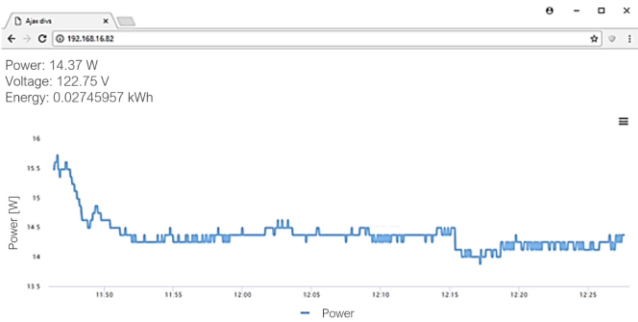
A multi-agent methodology [4][16][17] is used in order to set a distributed load consumption for a residential environment. An illumination circuit with LED and fluorescent lamps, appliance circuit with electric iron, and a multimedia circuit with a data network modem have been connected to the IoT SMN for operational testing. Figure 8 shows the measurement and testing process.

Fig. 8. Energy Consumption Metering with Illumination Circuit.

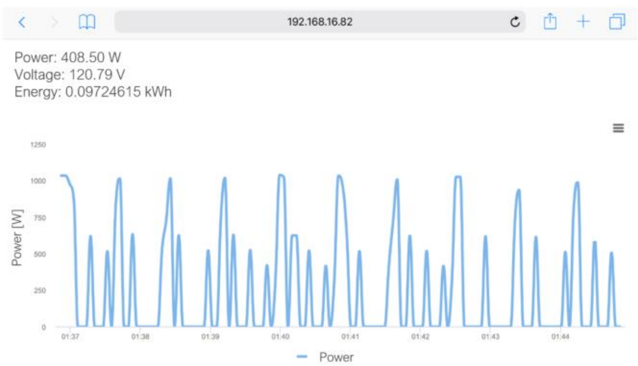
Figure 9 shows the consumption graphs obtained in the graphical interface that is achieved by developing web services on the Information Concentrator Node.



(a)



(b)



(c)

Fig.9. Consumption Metering Graphic Interface. (a) Illumination Circuit with Incandescent Lamp. (b) Illumination Circuit with Fluorescent and LED Lamps. (c) Appliance Circuit with Electric Iron.

As can be seen from Figure 9(c), the electric iron has a particular behavior and is one of the most powerful devices in a home testing case, so that tests are performed for short periods of time. In addition, the multimedia infrastructure has been analyzed, it includes consumption from Smart TV, Data Modem, Mini-component and Sound Devices. Table 3 shows the results obtained from consumption measurements for a residential environment.

Table 3. *IoT AMR System Operating Test Results*

Parameter	**Illum. C Incand.**	**Illum.C LED,Fl.**	**Appl.C. Iron**	**Multi-media**
Power [W]	60.00	15.00	800.00	400.00
Lower Peak [W]	58.84	14.13	0.00	90.00
Highest Peak [W]	62.90	15.70	1048.00	950.00
Voltage [V]	120-122	120-122	120-122	120-122
Consumption [kWh]	0.121	0.061	0.191	0.096
Test Time [h]	2	2	2	2

For information monitoring, the management elements corresponding to the devices that can connect to the IoT network have been used and the information of the artifact to be verified in a graphical interface such as: computers, tablets, smartphones, among others, have been used. The access interface for verifying prototype information supports multiple devices simultaneously connected to the Raspberry Pi-based Concentrator Node, as shown in Figure 10.

Fig.10. Power Management Tests on Multiple Smart Interface Devices

D. Results Analysis

The operating effectiveness of the prototype is 90% and has a margin of error of +/- 4.5 watts in each of the electrical power measurements that are made.

The success of communication and sending information between the Raspberry Pi server and the SONOFF POW meter and IoT Smart Meter Node (MCU ESP8266) confirms that the prototype meets the objectives that have been set.

The prototype system can store power data for up to 7 days, from devices powered on for 24 hours; after this time, it will continue to store the information, but the graph will be distorted. It is then necessary to discriminate the information to store in a secondary database for the development of additional services such as reporting, consumption management and facilities control.

Concurrency testing verifies that multiple end devices or IoT Node Interfaces can be simultaneously connected to the Raspberry Pi based Concentrator Node by deploying power data and graphics in real time without affecting prototypes performance and network communications.

The display of the information is multiplatform, since the system is compatible with any operating system: Win, iOS, Android, Linux, among others.

It is possible to measure loads simultaneously in the same IoT Smart Meter Node, connect, disconnect, add, or connect appliances and the prototype determines the corresponding electrical consumption by the total sum of the power consumed by all the elements connected.

In the case of turning off the prototype IoT SMN, the system will continue to function and store power data that will be 0 watts until the IoT SMN is restarted.

E. Data Network Architecture IoT AMR System.

In this case a framework for BEMS is introduced to optimize the use of building infrastructures ensuring minimum levels of comfort required by the users. The results are presented using a simulation using the Simscape tool. The model uses the Scheduler method that defines three states: prediction, monitoring supply and demand control in real time [12]. This model will also be considered as multi-agent, few variants like H-agent: monitors and controls the heating system (room level). V-agent: monitors and controls the ventilation system (room level). C-agent: monitors and controls the cooling system (room level). E-agent: monitors and controls electrical and lighting (room level) systems. U-agent: monitors and controls occupancy level and determines the load factors / weight agent's area [12]. It is also responsible for learning the preferences of users, their profiles, identification and feedback to the system.

F. Multi-Agent System Architecture for Smart Homes

Figure 11 shows the deployed data network architecture of the IoT node network to implement the AMR System.

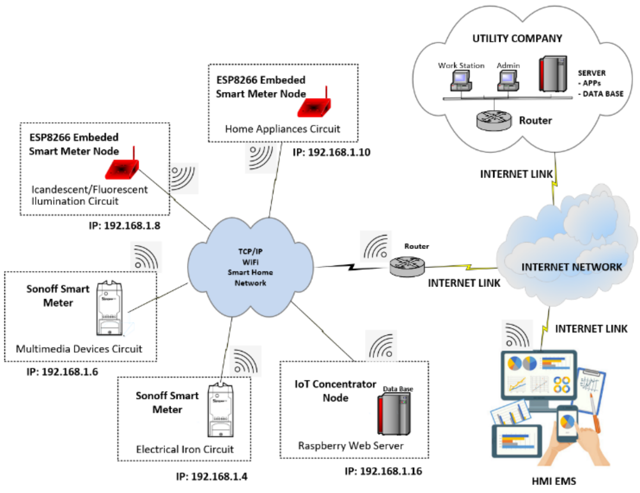


Fig.11. Data Network Architecture for IoT AMR System.

V. CONCLUSIONS

Technology analysis determined that the most optimal way to perform information transfer in Homes and Buildings is to use the WiFi communication protocol and programming languages such as PHP, that allows the integration of the IoT SMN with the Concentrator Node.

The prototype developed is easy to install, modular and expandable. For installation it is possible to use a surface connection on the wall, on DIN rail, in recessed box or conventional electrical board, as well as in a communications rack by means of a module of 6 units in which the measuring elements are fixed; all communications are wireless and only a connection to a 120 Volts unbroken power outlet is required.

The programming and interconnection between the IoT SMN and the platform allow the designer to deploy the user interface where all the data corresponding to power, voltage, consumption, and monitoring are displayed by graphs in real time. The prototype web interface is accessible using any operating system on different monitoring devices, which can be connected to the IP address of the Concentrator Node without the need for an application or license.

The prototype IoT SMN supports the connection of any electrical or electronic device simultaneously, as long as the sum of all its loads does not exceed a current flow of 16 Amps or 3500 Watts of power using an electrical network of 120-230 Volts.

The IoT SMN allows to integrate devices of all kinds such as electric consumption meters, environmental sensors, safety devices, automation and control, etc. This allows the designers to build Networks of IoT devices for the implementation of intelligent systems oriented to the field of home automation, Smart building, Smart Farming and Smart City.

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