Intelligent Distributed System for Energy Efficient Control

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Abstract. In this work, we present an intelligent system developed for energy consumption distributed control and monitoring. It supports real time cloud-based data visualization of power profiles from different areas, so as to optimize overall power consumption.

The local intelligent processing unit (LIPU) that control the different environments is described. The communication network model that allows connecting multiple LIPUs to apply power consumption policies defined by the organization is analyzed, and the unit's capabilities in relation to cloud connectivity and real-time processing are considered through a theoretical scalability study.

Finally, we describe relevant implementation features in the context of "Facultad de Informática" of the "Universidad Nacional de La Plata" (Argentine).

Keywords: Energy consumption, Intelligent Systems, Internet of Things, Cloud Computing, Optimization.

1 Introduction

Nowadays there is a high energy demand in society for carrying out daily work or personal activities. In particular, the amount of energy consumed in public and private institutions increases each year due to the high number of electric devices used. On the other hand, electricity comes with a elevated cost and any unnecessary consumption involves additional costs that could have been avoided. A clear example of this are educational institutions such as schools and universities.

Additionally, there is a growing concern for environment preservation, which is taking governments throughout the globe in a search for solutions that can counter these situations [1].

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According to the “Secretaría de Energía de la Nación” (SE), 87% of the primary energy consumed in Argentina comes from hydrocarbons. As a measure to reduce energy consumption, Decree 140/2007 proposes to reduce power consumption by 10% in public structures. Buildings account for around 40% of the final energy consumption and, as such, they offer a scenario with high potential to achieve significant reductions in energy consumption [2]. A highly energy-efficient building has a low environmental impact [3] while ensuring optimal interior conditions for the individuals, who spend more than 30% of their time in those spaces.

For these reasons, governments foster a set of policies and measures necessary to achieve energy savings in all sectors. An accurate knowledge of how much is actually consumed allows identifying unnecessary costs, optimizing the daily demand, balancing distributed loads and, as a consequence, decreasing energy consumption levels [4]. Then, power consumption can be optimized through the deployment of an intelligent system that collects information from building areas and act in consequence to save energy.

This system should consist of local intelligent processing units (LIPUs) that control the different environments and are connected to each other to obtain information for the entire building. The interconnecting network between these LIPUs should allow expanding the number of sectors that can be monitored within the building (or an area in it), and even consider groups of buildings. Toward this end, they could be connected to a server in the cloud that would be responsible for collecting the information from all separate buildings and areas.

Each LIPU needs a set or network of sensors that can detect events in the environment, such as the presence of people, temperature, devices connection status, and so forth. They should also have a set of actuators that allow controlling the state of the devices connected to the electrical power grid.

In this article, we explain the process used to develop the LIPUs as part of the Project “Unidad Inteligente para Control de Consumo Energético”, approved by the Secretaría de Políticas Universitarias (SPU) as a technology transfer project within the “Universidades Agregando Valor 2017” program, and describe the communications network that allows linking several LIPUs belonging to the same building or area in to apply energy consumption policies defined by the organization. Finally, cloud connection capabilities are considered as a tool for monitoring geographically distributed locations and collecting the information generated in each of them for cloud-based tools analysis.

2 Intelligent Distributed System for Energy Consumption Control in Organizations: The Project

As already mentioned, public and private institutions consume large volumes of energy, so they need to implement measures and use intelligent systems to achieve significant savings. In this article, we analyze the case of the Universidad Nacional de La Plata (UNLP), where the annual expense in energy consumption is 15% greater than the budget the University has assigned for non-salary expenses.

The UNLP consists of 17 schools with more than 100 buildings (including research, development and innovation units) and more than 1,200 physical spaces with diverse characteristics in relation to energy consumption requirements, such as:

- Classrooms: These are usually spacious rooms with plenty of lights, air-conditioning units, a projector, a computer and other elements. Generally, when the space is empty, all of these components can be turned off. On the other hand, they are laxly controlled and the electronic devices in them usually remain unnecessarily on.
- Offices: These are usually smaller spaces, with a few lights, an air-conditioning unit, several computers, a photocopier, and other elements. Generally, when the space is empty, all of these components can be turned off, except for the computers. They are more strictly controlled than classrooms, and usually electronic devices are not unnecessarily left on for long.
- Laboratories: These are usually small spaces, with a few lights, several air-conditioning units, a refrigerator/freezer, computers/servers, and other electronic equipment. In this case, none of these elements can be turned off, regardless of whether the space is empty or not.

Because of this, the UNLP is a good candidate to deploy and test an intelligent system to control power consumption. Taking into account the size and types of the spaces and the distribution of the buildings used by the UNLP, a layered system is appropriate. This requires considering at least 3 layers for the project (Figure 1 shows a diagram of these 3 layers and how they relate to each other):

- The local intelligent processing units (LIPUs) and the possibilities for the sensor network to which they are connected.
- The network connecting these LIPUs to a local server (LS), by floor and/or building, so as to be able to implement policies based on physical spaces as well as on blocks of spaces (for instance, floors in a building).
- The connection to a cloud server (CS) and the analysis of cloud-based services to process energy consumption in real time for each unit, sector in a building, buildings, and as a whole for a physically distributed organization such as the UNLP.

In each monitorable environment (classroom, laboratory, office, etc.), a LIPU must be installed, as seen on the lower level of the diagram in Fig. 1. Since each environment has different dimensions, the number of intelligent devices that are part of a LIPU is variable. There is a master device that is responsible for controlling the environment by gathering information about other devices that are part of that LIPU to generate sector control guidelines.

On the second level shown in Fig. 1, there is a LS for each separate building, floor or area that will be monitored. This LS collects data from all LIPUs in each area to obtain current consumption statistics for each environment and take the necessary general control actions to minimize unnecessary expenses.

On the upper level of the diagram in Fig. 1, there is a CS that collects all data from each LS for the different separate buildings, floors or areas (which could be geographically separated from each other). This allows using cloud-based services to help process the energy consumed by each environment, building, or as a whole, and obtain detailed information about the overall consumption of the entire University.

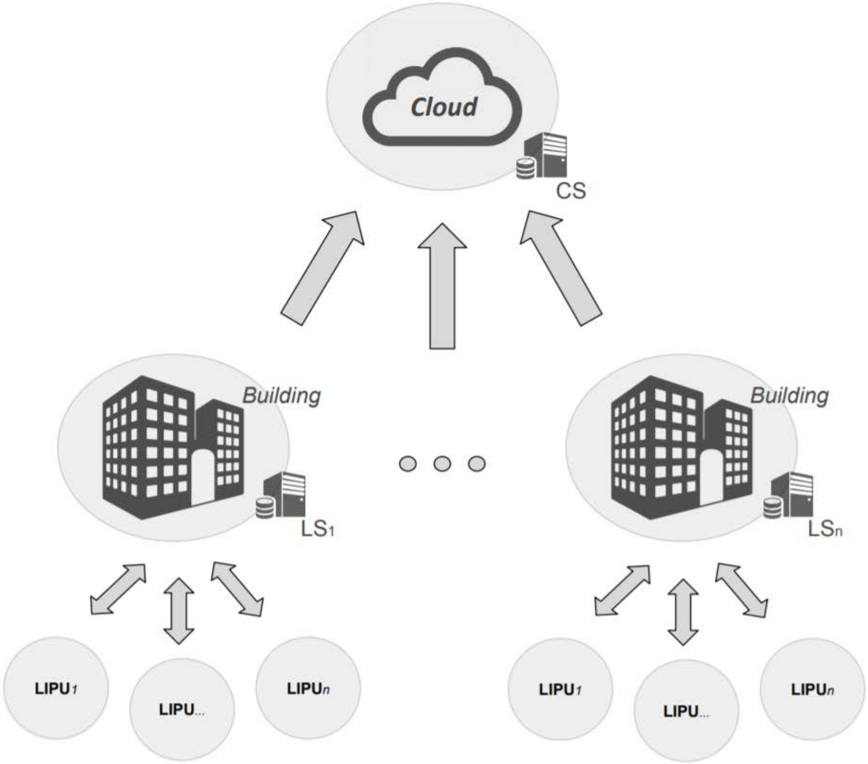

Fig. 1. Communication between the cloud and the geographically distributed buildings.

2.1 LIPUs Structure

A LIPU is composed by one or more hardware devices that offer a set of software functionalities, aimed at monitoring and controlling a number of electric components present in a given environment.

Since the scenarios have different dimensions, there are multiple devices interacting at the same time. There are two types of devices: masters and workers. Master devices are in charge of grouping, monitoring and controlling worker devices. Also, each master device can present functionalities that are similar to those offered by worker devices.

Fig. 2 shows a generic representation of the internal structure of the devices that are part of a LIPU.

Even though the figure encompasses the distribution of hardware components in master and worker devices, each of these two types usually has different arrangements and functionalities. Generally, master control devices have a programming interface and an LCD display, combined with a real-time clock and, eventually, certain functionalities that are similar to the ones present in worker devices. On the other hand, workers are only responsible for processing and communicating data to the master. In other words, master units can offer the same functionalities that a worker device has, with the difference that they also allow human-machine interaction. This interface allows configuring the environment to be controlled.

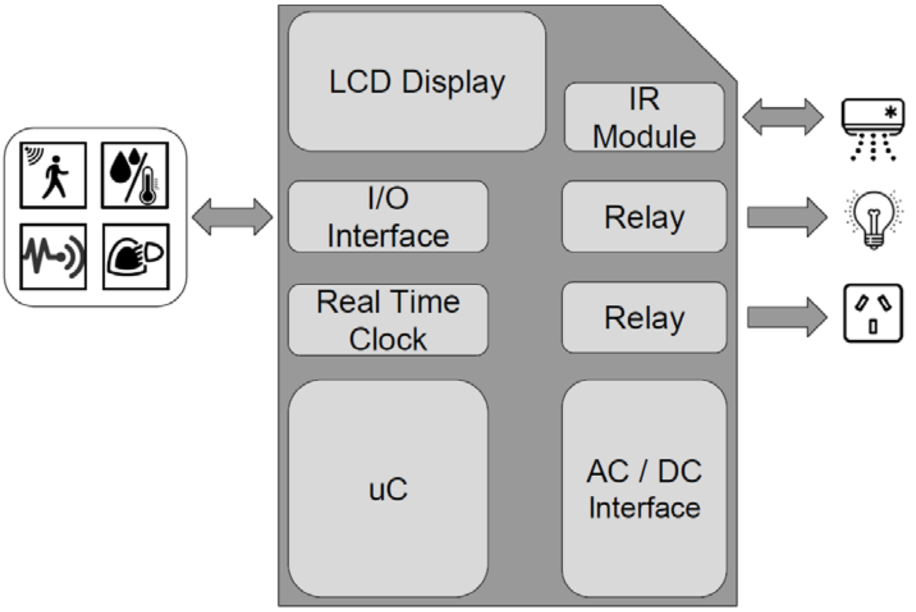

Fig. 2. Hardware diagram of LIPU components.

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As it can be seen, each device has an input/output interface that allows obtaining data from the different sensors, as well as executing different actions on a given electric device. With regard to input data, these units can be connected to different types of sensors that detect different variables such as presence, temperature, humidity, power current, luminosity, and so forth. The devices, otherwise, help to control the different electrical components through two output interfaces – relays and the infrared wave emitter. The former are electromagnetic devices that act as switches on an independent circuit, allowing turning the connected component on and off, for example, lights, power outlets, etc. Conversely, the IR emitter enables the wireless transmission of an on/off command for sophisticated devices where, turning them off forcibly (through relays) would directly affect their life time. An example of this type of devices are air-conditioning units. It should be noted that this IR module also supports learning from different infrared signals.

Unit processing and control is centralized on a micro-controller. This chip is also in charge of communicating all necessary data to the other devices in the environment. For this initial implementation, an ESP12 module was used. This micro-controller is based on the ESP8266 processor, which has various features, including Wi-Fi communication.

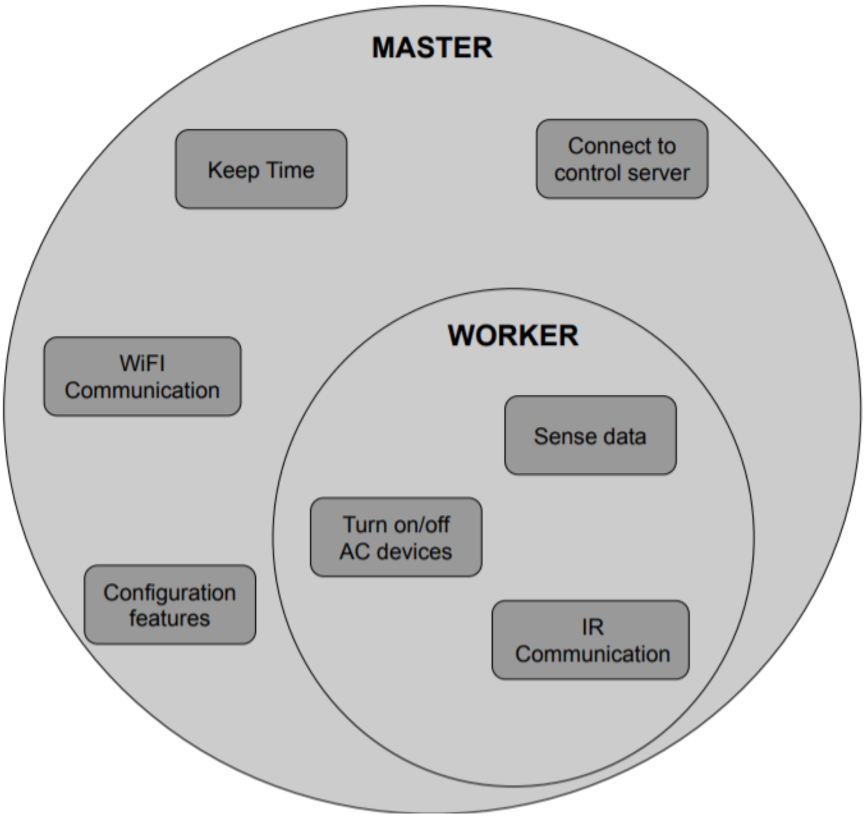

Fig. 3. Functionalities in a LIPU.

Master units can be programmed through a panel that has an LCD display, or using a Web application from a computer/tablet/mobile phone. Configurable functionalities include setting alarms, adding and removing sensors, defining events, adjusting the date, grouping relays, and so forth. Fig. 3 shows a brief description of software features present in the system. The processes that master and worker devices can run are analyzed, and the tasks that can be carried out only by the master device are identified.

The devices that are part of a LIPU are connected by means of a local Wi-Fi network generated by the master device controlling the LIPU. This allows connecting a variable number of workers, each of them controlling different sensors/actuators. Because of this, each worker configuration is customized through the corresponding Wi-Fi network. Since control is centralized, the different workers monitor events in the environment and send the information to the master device for decision making.

This topology facilitates scalability to differently-sized scenarios just by increasing the number of sensors in existing devices, or by adding new worker devices.

It should be noted that LIPU devices consume a maximum of two to three orders of magnitude lower than the electrical components that could be found in a standard classroom. Table 1 details energy consumption per hour (in Wh) of both devices (master and worker) in LIPUs, and that of basic electrical components.

Using this information, the energy savings that the intelligent system identifies for each hour that should be turned off can be estimated. For instance, in a relatively small classroom, with 4 fluorescent tubes, a projector and one air-conditioning unit, the LIPU for the classroom requires two devices (one master and one worker). During the day, the LIPU will consume a total maximum of 144Wh, which is compensated just by turning off the lights one hour during the day. If we take into account that there is also an air-conditioning unit and a projector, for each hour that the system establishes that all equipment should be turned off, more than 7500 Wh are saved (considering the consumption of these electronic devices).

Table 1. Energy consumption for various electronic devices.

	LIPU	Fluorescent tube	Projector	Air-conditioning unit
Energy consumption [Wh]	3	80	216	7300

2.2 Local Server (LS) in Each Building

One of the most common energy-related issues in buildings is the inefficient use of resources such as lights and electronic devices (air-conditioning units, fans, computers, projectors, and so forth). This can carry significant expenses and, eventually, result in various types of accidents due to device overheating and short-circuiting.

As a way to mitigate this issue, the LIPUs in a building or separate area can be grouped together so as to globally monitor and control all environments. To achieve this, there must be an existing wireless network covering the area delimited by the target scenarios, or a new one must be implemented. Being connected like this, the various master devices in the different LIPUs communicate the environment information and receive control parameters to act on it. The local server that centralizes control activities is implemented using a low-cost Raspberry Pi computer.

Building configuration is done through a Web system that integrates all environments and provides a simple interface for both global and specific customization for each environment. The system is coded using Python and the web framework Flask.

Toward this end, the system helps implement various control policies by allowing manual and automated settings. In the case of manual ones, they provide instant control over an environment, for example, to turn an electronic device on or off. On the other hand, it allows setting alarms (day/time to turn on/off a given electronic device), both sporadic and recurrent (for instance, weekly) for an automated control. Thus, each LIPU can act based on the information received from its connected sensors (mainly movement), or just by using a temporal restriction (alarms set).

Even though the system can be used for an entire building, it also provides a simple method to create a hierarchy of the structure to allow a layered approach to monitoring and configuration.

2.3 Cloud Server (CS)

The University needs to have centralized information about power consumption in its different buildings (or areas) to come up with suitable policies to optimize consumption. With the layers described in sections 2.1 and 2.2, this information is distributed among the different LSs, in detail. Therefore, a third layer is required for a CS to centralize this information, and a set of Amazon services to reduce information transfer from LSs to the CS and then process the information.

Service Architecture. A services architecture based on Amazon Web Service (AWS) public cloud is defined as part of the network of LIPUs and the LS in each building to help collect and process data, mainly focusing on power consumption measurements in each building. The AWS selected services are:

- *AWS IoT.* This service allows creating virtual devices on the cloud that represent the physical devices in the network, allowing two-way communication to collect data from the physical environment and send commands from the cloud.
  It allows working with different protocols, including HTTP and MQTT; as well as all necessary tools to define various security levels in the connection with each virtual device on the cloud [5].
  In our case, this service is used to represent on a virtual device each of the buildings where power consumption is being centrally measured.
- *AWS GreenGrass.* AWS GreenGrass allows taking the cloud environment to edge devices so that they can act locally with the data generated by the network of sensors to which they belong.
  This service is mainly used to pre-process the information generated by each of the components in the network, optimizing the number of packages that are sent to the cloud. This is particularly important, since Amazon services have a cost

  based on the flow of information; thus, when the number of packages sent is reduced by filtering out unnecessary data, general communication costs with the architecture will be lower as well [6].

  Specifically for our architecture, this service runs (on local servers) different algorithms to carry out the necessary operations to adapt the information that is uploaded to the cloud. Then, a secure connection is established with AWS IoT to transmit the information.

- *AWS Lambda.* This Amazon tool allows executing code on demand. An algorithm is developed to work on a set of specific data and, based on predefined events, the code to process it is triggered.

  AWS Lambda can be configured and used both on the cloud and on the local server within AWS GreenGrass core [7].

  In our case, it is used to filter data and calculate some additional data based on the information collected by each LIPU in the network for the building. This algorithm is run on the LS before establishing a connection to the CS.

Experiments and Results. The experiments carried out include the deployment of a LS on a Raspberry Pi 3 with Raspbian as operating system and running AWS GreenGrass and a local instance of AWS Lambda with several preset functions. On the other hand, a virtual device is defined within AWS IoT in the cloud to receive the data processed from the network of LIPUs synchronized with the GreenGrass core in the LS.

The first test consisted in creating two devices that are connected to GreenGrass, to help them communicate through the central server. To do this, we employ MQTT protocol with certificates for a secure connection.

Then, the test was escalated by applying a Lambda function that responds to received message events for each node and creates packages with both messages and then synchronizes from GreenGrass to the virtual device on the cloud.

These two basic scenarios were successful, and we proceeded then to create a service architecture tailored to the needs of the different networks of LIPUs deployed in different buildings.

After this, with the purpose of creating a real test scenario, two Lambda functions were developed to control two different communication capabilities – one of these functions is triggered whenever a LIPU sends a message to its LS, and the other is run once every hour (this period of time can be configured) to synchronize data with the virtual device representing the building on the cloud.

Two alternatives were considered for this experiment:

- Each LIPU sends a message on a regular basis with power consumption information to the central controller where GreenGrass is being run (on the LS for the corresponding building).
- GreenGrass synchronizes these data by sending a message, also on a regular basis, with the global average of the consumption for the building being monitored.

It should be noted that GreenGrass service period is considerably longer than that of local nodes.

This experiment was useful to establish various guidelines for the local message flow handling based on the type of data used by the system. Also, certificates were used to provide secure communications, both over the local Wi-Fi as well as over the connection with AWS IoT.

3 Conclusions and Future Work

The architecture and corresponding software for an intelligent processing unit to control a network of sensors have been developed. This process is oriented to a type of physical spaces and equipment typical of University environments (classrooms, laboratories). These low-cost units help achieve significant savings in energy consumption in this type of environments and, since they can be programmed, they can be tailored to different spaces and types of sensors.

A distributed, layered architecture has been defined that allows LIPUs from different floors or buildings to connect to a network and through it be linked in real time to the cloud. This configuration allows scaling the solutions to the entire University (in our case, UNLP) with the possibility of monitoring critical aspects related to energy consumption in each building.

Cloud services have been utilized and communication and response time tests have been carried out to analyze project viability, obtaining good results. Based on our research and the tests carried out on Amazon's public cloud services, it can be states that the service architecture proposed in this article is suitable for the needs and characteristics of the general system. These services allow considering a scalable and elastic architecture, where it is easy to increase both the number of nodes per building as well as the overall number of buildings. Since the information is centralized using AWS IoT, only a Core GreenGrass deployment is required and then connecting each LIPU to its corresponding server using the same settings and, most importantly, the same security policies that protect the integrity of communications.

Future lines of work include a monetary study in relation to the serial manufacture of the intelligent units for power consumption control; scaling up the tests to the entire Facultad de Informática, which has 3 floors with 25 classrooms and laboratories, 3 server rooms and about 15 administrative offices; and expanding the tests from one building to connecting LIPUs in at least 3 schools of the UNLP located throughout La Plata.

References

1. Martínez, F. J. R., Gómez, E. V.: Eficiencia energética en edificios: certificación y auditorías energéticas. Thomson-Paraninfo, Spain (2006).
2. Toranzo, E., Kuchen, E., Alonso-Frank, A.: Potenciales de eficiencia y confort para un mejor funcionamiento del edificio central de la universidad nacional de San Juan. AVERMA - Avances en Energías Renovables y Medio Ambiente 16(1), 157-164 (2012).

3. Pérez-Lombard, L., Ortiz, J., Pout, C.: A review on buildings energy consumption information. Energy and Buildings 40(3), 394-398 (2008).
4. Morán Álvarez, A.: Análisis y predicción de perfiles de consumo energético en edificios públicos mediante técnicas de minería de datos. Thesis of the University of Oviedo (2015).
5. Amazon Web Services IoT. https://aws.amazon.com/es/iot/, last accessed 2019/04/25.
6. Amazon Web Services IoT Greengrass. https://aws.amazon.com/es/greengrass/ last accessed 2019/04/28.
7. Amazon Web Services Lambda. https://aws.amazon.com/es/lambda/ last accessed 2019/05/02.