Scientific Paper / Artículo Científico

UNIVERSIDAD POLITÉCNICA SALESIANA ECUADOR
INGENIUS
Revista de Ciencia y Tecnología
https://doi.org/10.17163/ings.n24.2020.09
pISSN: 1390-650X / eISSN: 1390-860X

Monitoring Network to Automate the Cooling System of a Data Center

Red de monitorización para automatizar el sistema de enfriamiento de un centro de datos

José Ignacio Vega-Luna[1,*], Francisco Javier Sánchez-Rangel[1],
Gerardo Salgado-Guzmán[1], José Francisco Cosme-Aceves[1],
Víctor Noé Tapia-Vargas[1], Mario Alberto Lagos-Acosta[1]

Abstract

The objective of this work was to develop a monitoring network of temperature, humidity and air quality in a data center to automate the on and off switching of the cooling, ventilation and air filtering system using IoT (Internet of Things). A network with long-range wireless technology was implemented, consisting of five slave nodes, a master node and a user interface. The slave nodes periodically transmit the value of the three environment variables to the master node. The master node sends the information received from the slaves to a cloud server, so that it can be accessed from a user interface. When the value of any of the variables reaches the configured threshold, the cooling, ventilation and/or filtering system is activated as required. The tests showed that an accuracy of less than ±1.0 °C was obtained in the measurement of temperature, less than ±2 % in the measurement of humidity, less than ±8 μg/m^3 in the measurement of air quality and a range of 11.5 kilometers with line of sight was achieved in data transmission over the network. Based on these results, the network can be implemented to monitor sensors and processes in other facilities with this scope.

Keywords: Automation, data center, IoT, monitoring, temperature, wireless.

Resumen

El objetivo de este trabajo fue desarrollar una red de monitorización de temperatura, humedad y calidad del aire en un centro de datos para la automatización del encendido y apagado del sistema de enfriamiento, ventilación y filtrado de aire usando Internet de las cosas (IoT-Internet of Things). Se puso en marcha una red con tecnología inalámbrica de largo alcance compuesta por cinco nodos esclavo, un nodo maestro y una interfaz de usuario. Los nodos esclavo transmiten periódicamente al nodo maestro el valor de las tres variables de ambiente. El nodo maestro envía la información recibida de los esclavos a un servidor en la nube para poder ser accedida desde una interfaz de usuario. Cuando el valor de alguna de las variables alcanza el umbral configurado se enciende el sistema de enfriamiento, ventilación y/o filtrado de aire, según sea el caso. Las pruebas mostraron que se logró una precisión menor a ±1.0 °C en la medida de temperatura, menor a ±2 % en la medida de humedad, menor a ±8 μg/m^3 en la medida de la calidad del aire y un alcance de 11.5 kilómetros con línea de vista en la transmisión de datos en la red. Según estos resultados, la red puede ponerse en funcionamiento para la monitorización de sensores y procesos en otras instalaciones con este alcance.

Palabras clave: Automatización, centro de datos, inalámbrica, IoT, monitorización, temperatura.

[1,*]Área de Sistemas Digitales, Departamento de Electrónica, Universidad Autónoma Metropolitana-Azcapotzalco, Ciudad de México, México. Corresponding author ✉: vlji@azc.uam.mx.
http://orcid.org/0000-0002-4226-2936, http://orcid.org/0000-0002-4182-5856,
http://orcid.org/0000-0002-0581-7410, http://orcid.org/0000-0002-6875-5683,
http://orcid.org/0000-0002-1160-2432, http://orcid.org/0000-0003-0455-007X.

Received: 25-04-2020, accepted after review: 11-06-2020

Suggested citation: Vega-Luna, J. I.; Sánchez-Rangel, F. J.; Salgado-Guzmán, G.; Cosme-Aceves, J. F.; Tapia-Vargas, V. N. and Lagos-Acosta, M. A. (2020). «Monitoring Network to Automate the Cooling System of a Data Center». Ingenius. N.° 24, (july-december). pp. 87-96. doi: https://doi.org/10.17163/ings.n24.2020.09.

1. Introduction

Cooling, ventilation and air filtering are the three critical systems in the operation of a data center or data processing center (DPC). A room temperature increase may cause that the equipment housed in the DPC either stop operating, automatically shut down or even get damaged. The productivity of companies and institutions depends on the access and availability of the computer and telecommunication equipment for clients and users [1], which should be guaranteed by the operation of the DPC. In other words, if the applications are not in operation, the clients and users will not be able to do their work.

Nowadays, the monitoring of environment variables in most DPCs is carried out locally. A computer installed in the control office of the DPC receives the information from the sensors, commonly using an Ethernet segment or 2-Wire technology, and shows it in a user interface [2, 3]. This exhibits the following drawbacks: 1) Not all the surface of the DPC is covered because the sensors are installed at specific places; due to the limitation in the reach of the communication technology being used, it is not possible to access some points from the control office. 2) If for any reason or contingency any variable achieves the threshold value and remains in it for a long time, the only way through which the DPC administrator may know about it is visualizing it in the user interface. There is no mechanism that enables the administrator to react promptly to this eventuality when he or she is not in the control office. 3) In order to carry out the monitoring, as demanded by the audits nowadays, important changes in the user interface must be carried out to enable invoking it from the Internet [4].

This work was carried out on request of a data center. It was required to put into operation a wireless network for sensor monitoring. The network must consist of five slave nodes, strategically installed in the DPC, in charge of periodically measuring the values of temperature, humidity and concentration of PM2.5 particles, and transmitting them to a master node.

The functions of the master node must be: A) Send to a server in the cloud, the information received from the slave nodes. B) Implement the user interface through a web server whose page enables to online visualize the values of the three environment variables. C) If any variable reaches the configured threshold value, activate the cooling, ventilation of air filtering system, as required. D) If the value of a variable is equal to or greater than the threshold during an established time, a WhatsApp alert message must be sent to a mobile phone. E) The control system must be ON/OFF.

The implementation of the network should not require additional wiring nor modifying the one existing in the DPC. The distance from the farthest slave node to the master node is 300 meters.

The periodic monitoring of the variables from the Internet is because it is thus required by the companies and institutions that audit and certify the security and maintenance systems of the data centers [5, 6].

With the latest technological advances, a variety of radiofrequency communication technologies of great geographic coverage, low cost and low energy consumption have arisen; some of them were candidates to be used in the development of this work [7]. Some of these technologies are WiFi, Bluetooth Low Energy (BLE), ZigBee and LoRa (Long Range) [8].

The main features of the four previously mentioned wireless technologies are presented in the following.

The WiFi technology uses low cost transceivers, has a reach between 15 and 25 meters with line of sight, provides a large bandwidth and consumes a relatively high amount of electric power [9].

The BLE technology has a nominal reach of 100 meters with line of sight, provides a medium bandwidth and has low energy consumption [10, 11].

Regarding the ZigBee transceivers, these are low cost devices, with a range of 100 meters, low energy consumption and low bandwidth [12].

On the other hand, the LoRa technology uses low cost transceivers, provides a range of various kilometers with line of sight, has small bandwidth and low energy consumption [13].

Considering the previously mentioned features, it was decided to use the LoRa technology and develop a Low Power Wide Area Network (LPWAN) [14]. Lora is an open protocol developed by the LoRa Alliance that enables creating LPWAN networks for the Internet of Things (IoT) market [15]. The LoRa protocol defines the physical layer of the OSI model or wireless modulation to carry out the long distance communication, using low power radio transceivers that transmit small amounts of information at low speed, achieving a longer life time of the batteries [16].

In addition to the technological advances in wireless communications, the advent of sensors, actuators, microcontrollers and Internet service providers, has strongly boosted the development of IoT applications. The growth of the data centers has been promoted by trends such as IoT, Big Data, e-commerce and cloud use [17].

The monitoring network developed in this work consists of an LPWAN constituted by six nodes, five slaves and one master. The nodes were implemented using the Huzzah32-ESP32 card, which was chosen because it can be programmed using free and open source libraries of functions available in the cloud, which simplified the programming development since a complex low level language was not used.

Recent research works about the use of the LoRa technology, where a long range is required, have resulted in important advancements in different ambits of human life and process monitoring. For example, this technology has been applied in cities [18], smart homes [19] and buildings [20], farms and agricultural fields [21], healthcare [22] and hospitals, industrial processes [23], electric power consumption [24] and water [25], control of heating systems [26], security [27], fluids [28] and positioning [29], among others.

In parallel, a large number of sensor networks has been created during recent years for remote monitoring of environment parameters, mainly temperature, using IoT. Some of them have been applied in meteorology [30], smart buildings [31, 32], health systems [33], agriculture [34], industrial plants, thermoelectric plants [35] and steel production [36].

Similarly, an important number of applications has been implemented with networks of wireless sensors in data centers through IoT [37]. Most of them have concentrated in the monitoring and operation of cooling systems to achieve an efficient or reduced consumption of electric power [38] and water [39].

On the basis of the above, the benefits and contributions of the authors with the application developed are the following: 1) The monitoring of the variables is carried out remotely using recently developed IoT platforms in the cloud, which provide efficient, reliable and always available services for storing information and sending alert messages to a mobile phone. In most data centers this task is carried out locally, and they are migrating the monitoring to a solution similar to the one developed in this work. 2) It enables taking prompt actions before the occurrence of a contingency in the data center. 3) It fulfills a real need of the data center. 4) The network installation is non-intrusive, since it uses wireless communication and does not modify the wiring of the data center. 5) Its programming is based on free and open source libraries of functions, which reduces its installation time and complexity.

The following sections of this document describe the design, implementation and structure of the monitoring network, explain the tests carried out, as well as their purpose and the results achieved and, at last, present the conclusions obtained and the main recommendations.

2. Materiales y métodos

2.1. Materials and methods

The monitoring network is constituted by three elements: the slave nodes, the master node and the user interface. Figure 1 shows the functional diagram of the monitoring network.

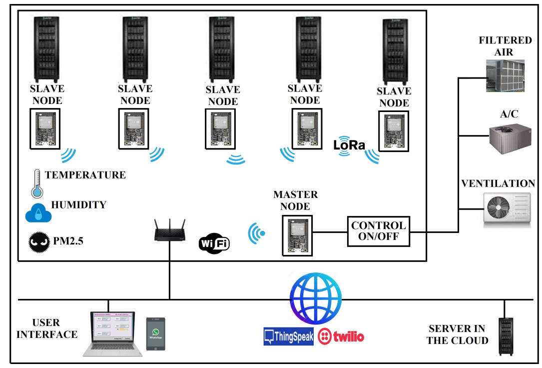

Figure 1. Functional diagram of the monitoring network.

2.2. The slave nodes

The five slave nodes were implemented using the architecture shown in Figure 2.

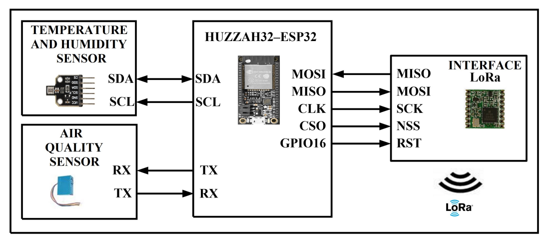

Figure 2. Architecture of the slave nodes.

The components used in each of these nodes were the Huzzah32-ESP32 card, the temperature and humidity sensor, the air quality sensor and the LoRa transceiver. The LoRa technology uses the functionalities of the physical layer, layer 1 of the OSI model, since it determines the type of modulation, the bandwidth and the frequency of the signal used in the network.

The used Huzzah32-ESP32 card has the resources required for the design of the slave nodes, thus reducing their size and cost. The main resources of the card are a Tensilica LX6 Microcontroller with two cores at 240 MHz, 4 MB of flash memory, 520 KB of RAM memory, WiFi 802.11b/g/n interfaces, classic and LE Bluetooth with integrated antenna, 3 UART ports, 3 SPI ports, 2 I^2C ports, 25 general purpose input/output (GPIO) and a lithium-ion battery charger.

The temperature and humidity sensor used in the slave nodes was the BME680 device. This digital device integrates four sensors, namely temperature, relative humidity, barometric pressure and gas, in a 3.0×3.0 mm^2 compact metallic packaging. It uses a supply voltage of 3.3 or 5 V, because the card on which it is mounted has a voltage regulator. It is used in automation applications in homes, offices, industries, IoT, weather forecast, air quality measurement and indoor navigation, among others. It has I^2C and SPI digital interfaces. The operating ranges are from –40 to +85 °C and from 0 to 100 % of relative humidity (RH). It can measure temperature with a precision of ±1.0 °C and humidity with an accuracy of ±3 %.

In the slave nodes, the communication between the BME680 and the microcontroller of the Huzzah32 card was carried out through the I^2C ports. The BME680 works as slave using the 0 × 77 address of the I^2C bus, to provide the value of temperature with a resolution of 20 bits, and the value of humidity with 16 bits. The barometric pressure and gas sensors of the BME680 were disabled to achieve a current consumption of only 2.1 µA and measure only temperature and humidity.

The PMS5003 sensor was used to measure the air quality in the slave nodes. This device measures the number of particles suspended in the air, i.e., the concentration of particles resulting from the operation of internal combustion engine vehicles, from fire generated by wood burning or from industrial processes. It is capable of measuring particles in the environment with diameters of 1, 2.5 and 10 microns, known as PM1.0, PM2.5 y PM10, respectively. Its operation is based on the dispersion of laser light which irradiates the particles suspended in the air, to capture the dispersed laser light and measure the number of particles by unit volume using a processor. The PMS5003 sensor has a UART serial port to digitally transmit the measurement of particles every second. It consumes less than 100 mA in active state and less than 200 µA in passive mode. It operates in the temperature range from −10 to +60 °C and in the humidity range from 0 to 99 % of RH, making it a good candidate to be used in the environment conditions of a data center. In the slave nodes, this sensor was connected to a UART port of the Huzzah32 card, which was configured to operate at a speed of 9,600 bps and measure PM2.5 particles.

The RFM95 circuit is the LoRa transceiver used in the slave nodes. This device has an SPI interface and its main operating features are the following: supply voltage of 3.3 V, output power from +5 to +20 dBm up to 100 mW, current consumption of 100 mA during transmission and 30 mA during active listening, reach of 2 km with line of sight with tuned unidirectional antennas or up to 20 km using directional antennas, RF transmission speed from 0.018 to 37.5 Kbps and transmission speed of the SPI of up to 300 Kbps. The RFM95 transceiver may be configured to be controlled from an external host through the SPI port. The host implements the communication interface between both devices using a master/slave protocol. In this work, the external host is the controller of the Huzzah32 card, which performs as the master, and the RFM95 transceiver performs as the slave. The interface has two types of messages: command packages and response packages. The master always sends command packages, while the slave always transmits response packages. When the master sends a package it should wait until the slave sends a response package, before transmitting another command package. The RFM95 transceiver is a slave, and cannot initiate a transaction with the master. The command packages consist of the following fields: preamble (4 bytes), start of frame (1 byte), type of command (1 byte), number of message (1 byte), length of the message (2 bytes), message (up to 256 bytes) and checksum to verify the integrity of the package (2 bytes). In the slave nodes, the SPI port of the RFM95 transceiver was connected to the SPI port of the Huzzah32 card. To achieve the reach required by the network, the RFM95 transceiver of the nodes uses an external antenna of gain type Omni Lora of 915 MHz, with the following features: gain 8 dBi, female type N connector, impedance 50 ohms and length 1.145 mm.

Regarding the programming of the Huzzah32 card of the slave nodes, it was carried out using the Arduino IDE development environment. The programming is responsible for executing tasks such as configuring the GPIO terminals and the I2C, UART and SPI ports, and initializing the RFM95 transceiver. Afterwards it should perform the reading, every 60 seconds, of the temperature (T), relative humidity and concentration of particles (PM2.5) to transmit it, through the LoRa transceiver, to the master node.

Two open source libraries were utilized to carry out the previous tasks: Adafruit_BME680.h to communicate the Huzzah32 card with the temperature and humidity sensor; Serial.h software to communicate the card with the air quality sensor, and RH_RF95.h and SPI.h for transmitting the information to the master node through the LoRa transceiver and the SPI port, respectively.

2.3. The master node

In a way similar to the slave nodes, the master node was developed using the Huzzah32-ESP32 card and the LoRa RFM95 transceiver. In addition, the master node integrates an electric interface between the Huzzah32 card and the actuators of the air filtering, ventilation and cooling equipment, as shown in the block diagram of the node architecture in Figure 3.

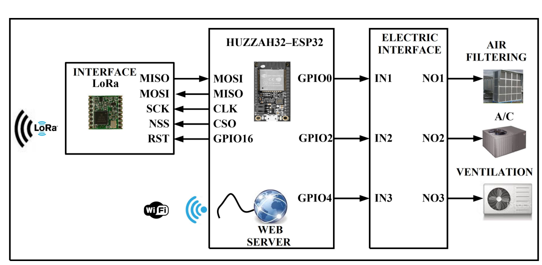

Figure 3. Architecture of the master node.

The functions of the master node were defined programming the Huzzah32 card so that it configures the GPIO terminals and the SPI port, and initializes the

RFM95 transceiver and the WiFi interface. Then, it invokes the function that starts the web server, which may be interrupted when receiving, through the SPI port, the information transmitted by the slave nodes.

The routine for serving the interruption is responsible for reading the information from the SPI port, and transmitting it to the server in the cloud. If the measured value of any of the environment parameters, T, RH or PM2.5 reaches the configured threshold, it activates the actuator of the corresponding equipment. For the case of the temperature the cooling or air conditioning (AC) equipment switches on; when the humidity reaches a maximum the air filtering mechanism is switched on, and when the concentration of particles is equal to or greater than 2.5 microns the ventilation equipment switches on. If the value of one or more of the previous parameters is equal to or greater than the threshold during a configured time, this routine transmits a WhatsApp alert message to the mobile phone through the Twilio service platform. When the value is again below the threshold, it switches off the equipment and transmits the corresponding WhatsApp message.

In addition to the open source libraries of functions used in the slave nodes, the following libraries were used in the programming of the master node: WiFi.h to carry out the communication with the WiFi interface and WebServer.h to implement the web server. Figure 4 illustrates the flow diagram used to develop the master node programming. The server in the cloud used in this work is available through the ThinkSpeak Internet service provider.

The electric interface between the Huzzah32 card and the A/C, air filtering and ventilation equipment was put into operation using a module of four channels of 3 V/125 VAC-250 VAC. This module integrates four SRD-03VDC-SL-C relays of one pole two throws and one optocoupler in each relay to isolate the digital circuit, in this case the Huzzah32 card, from the power circuit. The module relays are supplied with an input voltage of 3 V, and the input IN of each of them is activated from a GPIO terminal of the Huzzah32 card, configured as output, to switch on the equipment of the data center. The equipment actuators are connected to the normally open (NO) output of the corresponding relay, as shown in Figure 5.

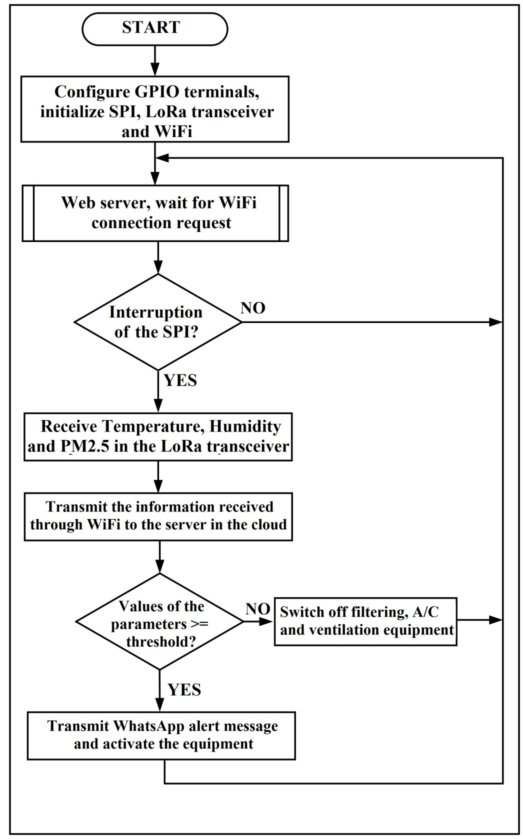

Figure 4. Flow diagram of the master node programming
.

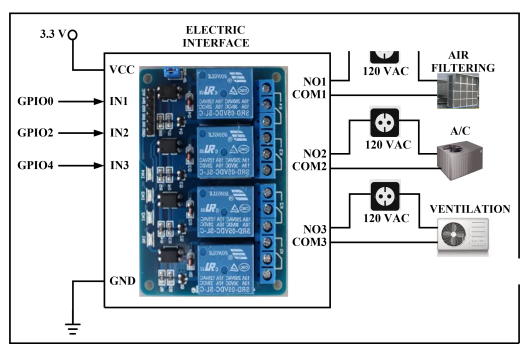

Figure 5. Electric interface of the master node .

2.4. The user interface

The user interface is a page developed with HTML, which is shown when the connection to the web server is established. Figure 6 shows the main page of the user interface through which the measured values of temperature, relative humidity and concentration of PM2.5 transmitted by each slave node, are visualized online.

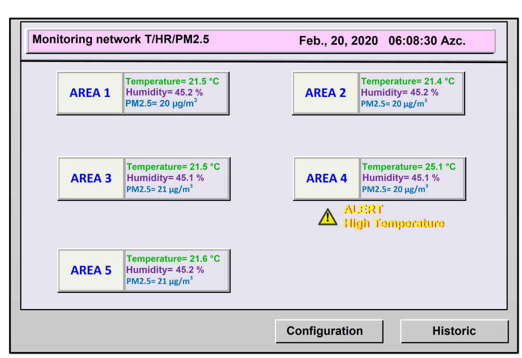

Figure 6. User interface.

For each slave node, there is a button in the interface under which an alert signal is indicated when the value of any of the parameters reach the threshold. When the button of one slave node is pressed, the user interface shows the real-time plot of the values obtained from ThinkSpeak, as shown in Figure 7.

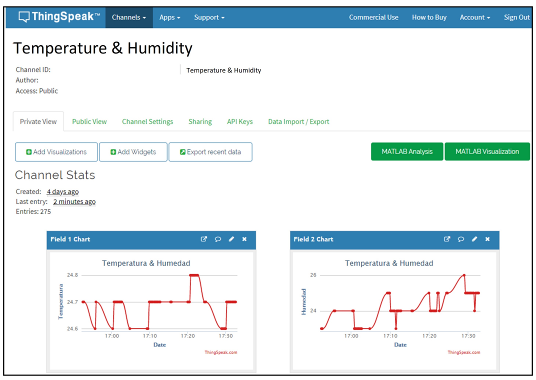

Figure 7. Plots of temperature and humidity in ThinkSpeak.

In addition, the interface has two buttons: Configuration, which enables to establish the number of mobile phone and threshold values for T, RH and PM2.5, and Historic, which can be used to download, from ThinkSpeak, the historic measured values of the parameters during a selected period of time, and store them in a text file. In general, this is the file requested during the audits to the data centers.

3. Results and discussion

Three groups of tests were conducted. The first group had the objective of determining the precision of the temperature measured by the monitoring network. To carry out these tests, the temperature in the sensor of a slave node was artificially set to different values, using a heater. Then, the temperature was measured around the slave node with an analog thermometer, similar to the one employed in the audits, and used as reference, i.e., this value was compared with the value reported in the user interface. The manufacturer of the BME680 sensor indicates a nominal precision of ±1.0 °C in the measured temperature [40]. The results of these tests showed that the real precision is smaller than ±1.0 °C which was maintained up to 68 ºC. When the temperature increases above this value, the difference between the value indicated in the thermometer and the one reported in the interface increased proportionally, as shown in Figure 8.

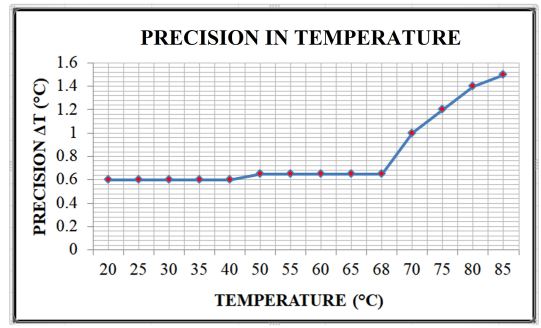

Figure 8. Precision in the measurement of temperature.

During the previous tests, there were no problems in the communication between the nodes of the network. The distance between the farthest slave node and the master node is 300 meters. However, a second group of tests was conducted to determine the reach of this network.

The signal transmitted by the nodes is subject to interferences, and is diffracted or absorbed in the medium; the reach of the network depends on the value of power established in the LoRa transceiver, environmental factors and obstacles in the signal route. The previous tests were carried out under the following conditions: with line of sight between the nodes, the RF transmission power in the RFM95 transceiver was configured to 20 dBm-100 mW, RF frequency 915 MHz, bandwidth BW 125 KHz and the temperature and relative humidity of the environment were 21.5 °C and 45.1 %, respectively.

When carrying out the second set of tests, a slave node was located at different distances from the master node with line of sight. The measurements reported in the user interface were verified at each location. The results of these tests indicated that the reach of the network is 11.5 kilometers with line of sight. At larger distances, the link between the slave node and the master node was lost. In this group of tests a program was developed and executed in the master node, to show the value of the Received Signal Strength Indication (RSSI) in the Arduino IDE. Results indicated that the attenuation of the RSSI value is significantly reduced after 9.2 kilometers, and continues to reduce constantly until the communication is lost at 11.5 kilometers, as indicated in Figure 9. In case of using this network in a place with different environmental conditions, it is recommended to conduct these tests to determine the reach limitations.

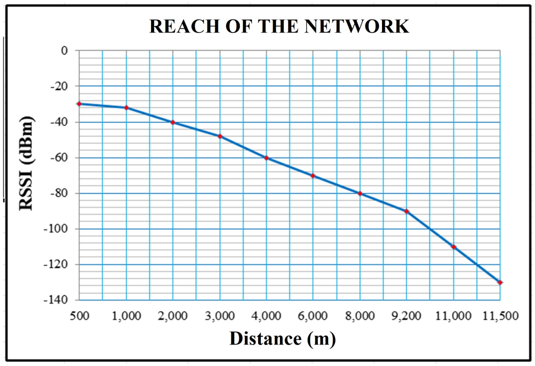

Figure 9. Reach of the network.

The purpose of the third group of tests was to verify the sending of WhatsApp alert messages. In these tests, smoke was artificially generated burning a piece of wood in the five slave nodes, to produce particles greater than 2.5 microns. The slave nodes reported the event in the user interface, and the message was correctly transmitted and received in the mobile phone with an approximate delay time of 1.75 seconds after the occurrence of the event. In both this set and in the first set of tests, one of the slave nodes reached the temperature threshold, as shown in Figure 10.

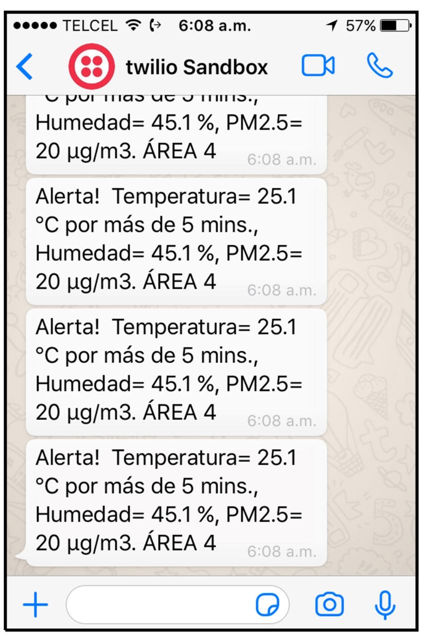

Figure 10. Alert message sent to the mobile phone.

4. Conclusions

Based on the results obtained it is concluded that the installation of the monitoring network is non-intrusive, since it is not necessary to install additional wiring for its operation; the reach of 11.5 kilometers is greater than the reach that can be achieved using traditional wireless technologies, sensors may be added to the slave nodes to access the information of other type of variables making slight changes in the programming.

The application developed here may be easily replied in other data centers or in other type of facilities, where it is necessary to remotely monitor processes using an IoT solution whose programming is based on free and open source software. It is recommended that a ThinkSpeak license is used if the monitoring time of the variables or processes is smaller than 30 seconds, because the amount of messages sent will exceed the maximum amount established in the software used in this work which has no cost.

In the short term, it is planned to work in two aspects of the system: to increase the reach of the network by integrating slave nodes configured as repeaters, and to develop a user interface which executes in mobile devices.

References

[1] X. Ma, Z. Zhang, and S. Su, "Cost-aware multi-domain virtual data center embedding," *China Communications*, vol. 15, no. 12, pp. 190–207, 2018. [Online]. Available: https://bit.ly/2XT3VUB

[2] C. Sun, Y. Wen, P. Li, W. Ye, J. Yang, J. Qiu, and J. Wen, "Self-contained wireless hall current sensor applied for two-wire zip-cords," *IEEE Transactions on Magnetics*, vol. 52, no. 7, pp. 1–4, 2016. [Online]. Available: https://doi.org/10.1109/TMAG.2016.2524671

[3] S. Baig, W. Iqbal, J. L. Berral, A. Erradi, and D. Carrera, "Real-time data center's telemetry reduction and reconstruction using markov chain models," *IEEE Systems Journal*, vol. 13, no. 4, pp. 4039–4050, 2019. [Online]. Available: https://doi.org/10.1109/JSYST.2019.2918430

[4] G. Zhabelova, M. Vesterlund, S. Eschmann, Y. Berezovskaya, V. Vyatkin, and D. Flieller, "A comprehensive model of data center: From cpu to cooling tower," *IEEE Access*, vol. 6, pp. 61 254–61 266, 2018. [Online]. Available: https://doi.org/10.1109/ACCESS.2018.2875623

[5] SEGOB, *Declaratoria de vigencia de la Norma Mexicana NMX-C-506-ONNCCE-2015*. Diario Oficial de la Federación. Secretaría de Gobernación. México., 2015. [Online]. Available: https://bit.ly/2BYWOS1

[6] TIA. (2019) Tia launches ansi/tia-942 accreditation scheme for certification of data centers, selects certac to manage program. [Online]. Available: https://bit.ly/2XTtgxB

[7] Q. Ren, L. Wang, J. Huang, C. Zhang, and Q. Huang, "Simultaneous remote sensing of temperature and humidity by lc-type passive wireless sensors," *Journal of Microelectromechanical Systems*, vol. 24, no. 4, pp. 1117–1123, 2015. [Online]. Available: https://doi.org/10.1109/JMEMS.2014.2384591

[8] C. Jiang, Y. Qiu, H. Gao, T. Fan, K. Li, and J. Wan, "An edge computing platform for intelligent operational monitoring in internet data centers," *IEEE Access*, vol. 7, pp. 133 375–133 387, 2019. [Online]. Available: https://doi.org/10.1109/ACCESS.2019.2939614

[9] M. Ayaz, M. Ammad-uddin, I. Baig, and E. M. Aggoune, "Wireless sensor's civil applications, prototypes, and future integration possibilities: A review," *IEEE Sensors Journal*, vol. 18, no. 1, pp. 4–30, 2018. [Online]. Available: https://doi.org/10.1109/JSEN.2017.2766364

[10] S. Yu, P. Feng, and N. Wu, "Passive and semi-passive wireless temperature and humidity sensors based on epc generation-2 uhf protocol," *IEEE Sensors Journal*, vol. 15, no. 4, pp. 2403–2411, 2015. [Online]. Available: https://doi.org/10.1109/JSEN.2014.2375180

[11] D. Morrison, T. Ablitt, and J. Redouté, "Miniaturized low-power wireless sensor interface," *IEEE Sensors Journal*, vol. 15, no. 9, pp. 4731–4732, 2015. [Online]. Available: https://doi.org/10.1109/JSEN.2015.2442235

[12] J. Chou, J. Chen, Y. Liao, C. Lai, R. Chen, Y. Tsai, C. Lin, J. Chen, M. Huang, and H. Chou, "Wireless sensing system for flexible arrayed potentiometric sensor based on xbee module," *IEEE Sensors Journal*, vol. 16, no. 14, pp. 5588–5595, 2016. [Online]. Available: https://doi.org/10.1109/JSEN.2016.2570285

[13] T. Wang, Z. Su, Y. Xia, and M. Hamdi, "Rethinking the data center networking: Architecture, network protocols, and resource sharing," *IEEE Access*, vol. 2, pp. 1481–1496, 2014. [Online]. Available: https://doi.org/10.1109/ACCESS.2014.2383439

[14] O. Georgiou and U. Raza, "Low power wide area network analysis: Can lora scale?" *IEEE Wireless Communications Letters*, vol. 6, no. 2, pp. 162–165, 2017. [Online]. Available: https://doi.org/10.1109/LWC.2016.2647247

[15] Q. Zhou, K. Zheng, L. Hou, J. Xing, and R. Xu, "Design and implementation of open lora for iot," *IEEE Access*, vol. 7, pp. 100 649–100 657, 2019. [Online]. Available: https://doi.org/10.1109/ACCESS.2019.2930243

[16] T. Elshabrawy and J. Robert, "Interleaved chirp spreading lora-based modulation," *IEEE Internet of Things Journal*, vol. 6, no. 2, pp. 3855–3863, 2019. [Online]. Available: https://doi.org/10.1109/JIOT.2019.2892294

[17] B. Buurman, J. Kamruzzaman, G. Karmakar, and S. Islam, "Low-power wide-area networks: Design goals, architecture, suitability to use cases and research challenges," *IEEE Access*, vol. 8, pp. 17 179–17 220, 2020. [Online]. Available: https://doi.org/10.1109/ACCESS.2020.2968057

[18] M. Sidorov, P. V. Nhut, Y. Matsumoto, and R. Ohmura, "Lora-based precision wireless structural health monitoring system for bolted joints in a smart city environment," *IEEE Access*, vol. 7, pp. 179 235–179 251, 2019. [Online]. Available: https://doi.org/10.1109/ACCESS.2019.2958835

[19] G. Premsankar, B. Ghaddar, M. Slabicki, and M. Di Francesco, "Optimal configuration of lora networks in smart cities," *IEEE Transactions on Industrial Informatics*, pp. 1–1, 2020. [Online]. Available: https://doi.org/10.1109/TII.2020.2967123

[20] W. Xu, J. Y. Kim, W. Huang, S. S. Kanhere, S. K. Jha, and W. Hu, "Measurement, characterization, and modeling of lora technology in multifloor buildings," *IEEE Internet of Things Journal*, vol. 7, no. 1, pp. 298–310, 2020. [Online]. Available: https://doi.org/10.1109/JIOT.2019.2946900

[21] S. Benaissa, D. Plets, E. Tanghe, J. Trogh, L. Martens, L. Vandaele, L. Verloock, F. A. M. Tuyttens, B. Sonck, and W. Joseph, "Internet of animals: characterisation of lora sub-ghz off-body wireless channel in dairy barns," *Electronics Letters*, vol. 53, no. 18, pp. 1281–1283, 2017. [Online]. Available: https://doi.org/10.1049/el.2017.1344

[22] F. Wu, J. Redouté, and M. R. Yuce, "We-safe: A self-powered wearable iot sensor network for safety applications based on lora," *IEEE Access*, vol. 6, pp. 40 846–40 853, 2018. [Online]. Available: https://doi.org/10.1109/ACCESS.2018.2859383

[23] J. P. Shanmuga Sundaram, W. Du, and Z. Zhao, "A survey on lora networking: Research problems, current solutions, and open issues," *IEEE Communications Surveys Tutorials*, vol. 22, no. 1, pp. 371–388, 2020. [Online]. Available: https://doi.org/10.1109/COMST.2019.2949598

[24] A. Javed, H. Larijani, and A. Wixted, "Improving energy consumption of a commercial building

with iot and machine learning," *IT Professional*, vol. 20, no. 5, pp. 30–38, 2018. [Online]. Available: https://doi.org/10.1109/MITP.2018.053891335

[25] O. Khutsoane, B. Isong, N. Gasela, and A. M. Abu-Mahfouz, "Watergrid-sense: A lora-based sensor node for industrial iot applications," *IEEE Sensors Journal*, vol. 20, no. 5, pp. 2722–2729, 2020. [Online]. Available: https://doi.org/10.1109/JSEN.2019.2951345

[26] L. Zhao, W. Wu, and S. Li, "Design and implementation of an iot-based indoor air quality detector with multiple communication interfaces," *IEEE Internet of Things Journal*, vol. 6, no. 6, pp. 9621–9632, 2019. [Online]. Available: https://doi.org/10.1109/JIOT.2019.2930191

[27] P. Kulkarni, Q. O. A. Hakim, and A. Lakas, "Experimental evaluation of a campus-deployed iot network using lora," *IEEE Sensors Journal*, vol. 20, no. 5, pp. 2803–2811, 2020. [Online]. Available: https://doi.org/10.1109/JSEN.2019.2953572

[28] L. Leonardi, F. Battaglia, and L. Lo Bello, "Rt-lora: A medium access strategy to support real-time flows over lora-based networks for industrial iot applications," *IEEE Internet of Things Journal*, vol. 6, no. 6, pp. 10 812–10 823, 2019. [Online]. Available: https://doi.org/10.1109/JIOT.2019.2942776

[29] K. Lam, C. Cheung, and W. Lee, "Rssi-based lora localization systems for large-scale indoor and outdoor environments," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 12, pp. 11 778–11 791, 2019. [Online]. Available: https://doi.org/10.1109/TVT.2019.2940272

[30] R. I. S. Pereira, S. C. S. Jucá, P. C. M. Carvalho, and C. P. Souza, "Iot network and sensor signal conditioning for meteorological data and photovoltaic module temperature monitoring," *IEEE Latin America Transactions*, vol. 17, no. 06, pp. 937–944, 2019. [Online]. Available: https://doi.org/10.1109/TLA.2019.8896816

[31] X. Zhang, M. Pipattanasomporn, T. Chen, and S. Rahman, "An iot-based thermal model learning framework for smart buildings," *IEEE Internet of Things Journal*, vol. 7, no. 1, pp. 518–527, 2020. [Online]. Available: https://doi.org/10.1109/JIOT.2019.2951106

[32] L. Zhao, W. Wu, and S. Li, "Design and implementation of an iot-based indoor air quality detector with multiple communication interfaces," *IEEE Internet of Things Journal*, vol. 6, no. 6, pp. 9621–9632, 2019. [Online]. Available: https://doi.org/10.1109/JIOT.2019.2930191

[33] M. M. Alam, H. Malik, M. I. Khan, T. Pardy, A. Kuusik, and Y. Le Moullec, "A survey on the roles of communication technologies in iot-based personalized healthcare applications," *IEEE Access*, vol. 6, pp. 36 611–36 631, 2018. [Online]. Available: https://doi.org/10.1109/ACCESS.2018.2853148

[34] J. Ruan, Y. Wang, F. T. S. Chan, X. Hu, M. Zhao, F. Zhu, B. Shi, Y. Shi, and F. Lin, "A life cycle framework of green iot-based agriculture and its finance, operation, and management issues," *IEEE Communications Magazine*, vol. 57, no. 3, pp. 90–96, 2019. [Online]. Available: https://doi.org/10.1109/MCOM.2019.1800332

[35] Q. Wan, Y. Teh, Y. Gao, and P. K. T. Mok, "Analysis and design of a thermoelectric energy harvesting system with reconfigurable array of thermoelectric generators for iot applications," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 64, no. 9, pp. 2346–2358, 2017. [Online]. Available: https://doi.org/10.1109/TCSI.2017.2708763

[36] Y. Han, C. Zhang, L. Wang, and Y. Zhang, "Industrial iot for intelligent steelmaking with converter mouth flame spectrum information processed by deep learning," *IEEE Transactions on Industrial Informatics*, vol. 16, no. 4, pp. 2640–2650, 2020. [Online]. Available: https://doi.org/10.1109/TII.2019.2948100

[37] C. Yang, D. Puthal, S. P. Mohanty, and E. Kougianos, "Big-sensing-data curation for the cloud is coming: A promise of scalable cloud-data-center mitigation for next-generation iot and wireless sensor networks," *IEEE Consumer Electronics Magazine*, vol. 6, no. 4, pp. 48–56, 2017. [Online]. Available: https://doi.org/10.1109/MCE.2017.2714695

[38] K. Kaur, S. Garg, G. Kaddoum, E. Bou-Harb, and K. R. Choo, "A big data-enabled consolidated framework for energy efficient software defined data centers in iot setups," *IEEE Transactions on Industrial Informatics*, vol. 16, no. 4, pp. 2687–2697, 2020. [Online]. Available: https://doi.org/10.1109/TII.2019.2939573

[39] L. Yang, Y. Deng, L. T. Yang, and R. Lin, "Reducing the cooling power of data centers by intelligently assigning tasks," *IEEE Internet of Things Journal*, vol. 5, no. 3, pp. 1667–1678, 2018. [Online]. Available: https://doi.org/10.1109/JIOT.2017.2783329

[40] Bosch, "Gas sensor measuring relative humidity, barometric pressure, ambient temperature and gas (VOC) BME680," Bosch Sensortec GmbH 2020, Tech. Rep., 2017. [Online]. Available: https://bit.ly/2YlAvNS