A forest fire monitoring and detection system based on wireless sensor networks

Sistema de monitorización y detección de incendios forestales basado en redes de sensores inalámbricos

J. A. Castro-Correa; S. B. Sepúlveda-Mora; B. Medina-Delgado; C. D. Escobar-Amado; D. Guevara-Ibarra

DOI: https://DOI.org/10.22517/23447214.24784
Scientific and technological research article

***Abstract*— Global climate change is affecting Earth in various ways, including glacial detachment, sea-level rise, and more intense heat waves, which in turn contribute to fires in areas rich in flora and fauna, causing erosion and changes in plant and animal ranges. Despite international efforts to mitigate climate change, the problem remains uncontrolled in many areas. In this study, a forest fire monitoring and early warning system is proposed. It is based on a wireless sensor network (WSN) that measures the environment to detect and prevent fires in rural areas. The WSN uses open-access technologies and the Zigbee standard for radiofrequency communication and sends collected data to a web server via GPRS and TCP/IP protocol. The WSN's performance is evaluated using two metrics: data transmission rate and time delay. The WSN achieved an average success rate of data transmission greater than 86% with an average time delay of less than 500 milliseconds in all tests, demonstrating the potential of WSNs as near real-time forest fire detection systems.**

***Index Terms*— Arduino, forest fires, Raspberry Pi, wireless sensor networks, Zigbee.**

***Resumen*— El cambio climático global está afectando a la Tierra de diversas maneras, como el desprendimiento de glaciares, la subida del nivel del mar y olas de calor más intensas, que a su vez contribuyen a los incendios en zonas ricas en flora y fauna, provocando erosión y cambios en las áreas de distribución de plantas y animales. A pesar de los esfuerzos internacionales por mitigar el cambio climático, el problema sigue sin controlarse en muchas zonas. En este estudio se propone un sistema de vigilancia y alerta temprana de incendios forestales. Se basa en una red de sensores inalámbricos (WSN) que mide el entorno para detectar y prevenir incendios en zonas rurales. La WSN utiliza tecnologías de acceso abierto y el estándar Zigbee para la comunicación por radiofrecuencia y envía los datos recogidos a un servidor web mediante GPRS y protocolo TCP/IP. El rendimiento de la WSN se evalúa utilizando dos métricas: la tasa de transmisión de datos y el retardo temporal. La WSN logró una tasa media de éxito en la transmisión de datos superior al 86% con un retardo medio inferior a 500 milisegundos en todas las pruebas, lo que demuestra el potencial de las WSN como sistemas de detección de incendios forestales casi en tiempo real.**

***Palabras claves*— Arduino, incendios forestales, Raspberry Pi, redes de sensores inalámbricos, Zigbee.**

This manuscript was sent on June 28, 2021 and accepted on March 22, 2022. This work was supported by Colciencias under the call "Jóvenes investigadores e innovadores" 812-2018, and contract 069-2019 granted by Francisco de Paula University.

Jhon A. Castro-Correa is with Francisco de Paula Santander University, Cúcuta, Colombia (email: jhonalejandrocc@ufps.edu.co)

Sergio B. Sepúlveda-Mora is with Francisco de Paula Santander University, Cúcuta, Colombia (email: sergio.sepulveda@ufps.edu.co)

Byron Medina-Delgado is with Francisco de Paula Santander University, Cúcuta, Colombia (email: byronmedina@ufps.edu.co)

Christian D. Escobar-Amado is with the University of Delaware, Newark, DE 19716 USA (email: escobarc@udel.edu)

Dinael Guevara-Ibarra is with Francisco de Paula Santander University, Cúcuta, Colombia (email: dinaelgi@ufps.edu.co)

I. Introduction

GLOBAL climate change is a long-term shift in climate patterns that produces undesirable effects on the planet. The temperature and sea-level rise yield natural phenomena whose occurrence severely devastates the environment. One of the direct incidences of climate change is the forest fires, in which large vegetation areas are burned due to combustion reactions. Although climate change is not the solely cause of forest fires, it is the main cause of their generation and propagation. As an effort to reduce the negative effects of climate change, most of the countries around the world signed the Paris agreement in 2016 to implement friendly environmental practices [1]. Even though the Paris agreement marked a big step for the environment conservation, additional strategies involving technologies need to be considered to address the problem from a different perspective. As an alternative to prevent fires in rural zones, in this paper we introduce a forest fire monitoring and detection system based on wireless sensor networks (WSNs). The system implemented is easily scalable and is comprised of open-access and low-cost technologies.

Permanent east-to-west prevailing winds flowing in the equatorial region alter ocean temperature and have impacts on the weather all over the globe. Every year, such fluctuations in the water are provoked by two opposite climate patterns, El Niño and La Niña. Those two events have global impacts on weather, wildfires, ecosystems, and economies. According to the 2020 global climate report from the national oceanic and atmospheric administration (NOAA), 2020 was, in general, the second-warmest year, and land areas were the hottest in the 141-record, where the upward trend in the globally averaged temperature shows that more areas are warming than cooling [2].

Fire is a common and natural part of many wild landscapes. However, global warming changes the underlying variables that make fires more likely to occur every year. An increment in the temperature raises the likelihood that fires propagate on more extensive areas, severely affecting the surrounding lands and population near the conflagration area. The uncontrollable proliferation of forest fires contributes to negative effects on ecosystems. Fire is not limited to devastating vegetation but produces an irreversible impact on the soil, which is degraded to the erosion point. The cycles of their occurrence shorten rapidly during the dry season, which, combined with other factors (climatic, edaphological, and human activity) lead to situations of very high-risk [3]. As a result of these events, the implementation of intergovernmental agreements and technological alternatives are required to reduce the fires incidence on the planet. Novel advances in electronics and computing have become strong candidates for solving problems in different areas. Some examples are artificial intelligence, renewable energy systems, and the Internet of things (IoT), in which small devices connected to the Internet work together to carry out a specific application [4]–[6].

The development of the IoT as a paradigm yields to think of new concepts such as *smart cities*, *green cities*, and *smart transport and energy transmission* [7]–[9]. These complex systems are made up of small and interconnected devices that perform common tasks by using the Internet as the mean of communication. Those advances are broadly used to solve a wide variety of problems. The use of the Internet of things allows the user to remotely access monitoring devices from any service connected to the Internet in a dynamic, fast, and safe manner. The IoT also offers great portability and large-scale integration options. Recently, the IoT is presented as a cheap and secure alternative for the treatment of information in real-time, permitting a great flexibility for the implementation of one, hundreds or even thousands of devices (nodes) simultaneously, thus allowing a greater range of coverage by the nodal alert system [10]–[12]. In the case of forest fires, it is possible to use systems based on WSNs to early-detect these events. A WSN is a network made up of various devices interconnected by radiofrequency [13]–[15]. The WSNs are a subset of the IoT since although they integrate simple devices that work together to develop a specific task, they are not necessarily connected to the Internet. Those WSNs collect data from the surrounding environment, include large scalability, low-power consumption, high performance, and real-time wireless environmental monitoring [13], [16], [17].

The development of novel technological alternatives to prevent and early-detect forest fires have been addressed in the past using different methods and techniques. In India, different systems based on optical fire sensors, satellite-based methods, and wireless sensor networks were explored, evidencing big benefits for forest fire monitoring applications [18], [19]. The authors in [20], deployed a WSN based on a low energy adaptive clustering hierarchy (LEACH) system, which led to effective communication using a device that worked optimally for temperatures above a fixed threshold. In Cúcuta, a WSN was developed for the optimal deployment of nodes in a cocoa crop considering the type of antenna and the position of the nodes [21], whereas an error-detection system was also implemented to report in almost real-time to a mobile application [22]. A WSN was proposed in China to prevent fires using software based on the triangular fuzzy number (F-AHP), combined with a Monte Carlo algorithm to improve the performance level of the code [23]. Researchers in [24], implemented a network of sensors for the supervision of environmental variables in greenhouses using a modular and reduced design suited to the environment. These implementations demonstrate the versatility of the WSNs for multiple applications related to in-situ measurements. In this work, we present a WSN to early-detect forest fires based on the TCP/IP protocol, open-source technologies, free software and the Zigbee standard, an IEEE 802.15.4-based specification for a suite of high-level communication protocols.

This paper is structured as follows; in section II we present the methodology used to implement the WSN. Section III reports results for time delay and delivery package ratio obtained through measurements of the WSN, followed by the conclusions in section IV.

II. Methods

In this section, we discuss the methodology used to develop and deploy the wireless sensor network. The implemented WSN corresponds to a tree-like topology and consists of a coordinator node, routers, and end devices. The WSN prototype sends the collected data to a dedicated web server via TCP/IP protocol and is thought for its implementation in rural zones closed to Cúcuta, Colombia.

A. Wireless sensor network

Wireless sensor networks are meant to monitor physical or environmental conditions using wirelessly interconnected nodes. The most common WSN architectures are the star, tree, and mesh topologies, which incorporate three different devices, coordinators, routers, and end devices. The coordinator node receives and controls the flow of data coming from the rest of the devices. The end devices only measure and transmit data, while the router nodes measure data and serve as a link between the coordinator and the end devices. In most cases, for a WSN to properly work, at least a coordinator node, along with either routers or end devices must be included in the architecture. In this work, a WSN was designed and implemented using the Zigbee standard considering several steps.

The first step taken was the choice of the sensor network architecture to use. Among the three most popular wireless sensor network architectures, a tree-like topology was selected for the development of the prototype. The previous consideration was based on the simplicity of the network, the surrounded environment, and the expansion capacity in large areas. The incorporation of one single coordinator node permits the easy communication of the WSN with a web server on the Internet. An example of the implemented tree-like WSN is shown in Fig. 1. This WSN was composed of three main components. The coordinator node (ZC) that controls the flow of data in the network; the end devices (ZED), responsible for measuring data; and the router nodes (ZR), which take samples and in addition establish communication between the end devices and the coordinator node.

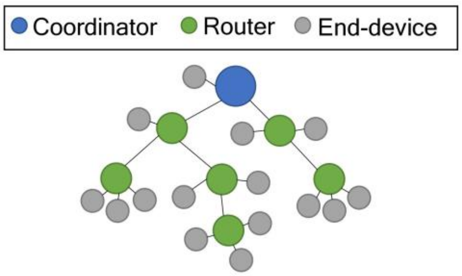

Fig. 1. Tree topology of a wireless sensor network. This architecture incorporates a coordinator node, routers, and end devices.

The internal communication between nodes in the WSN was exclusively based on radiofrequency using XBee S2C devices working on top the IEEE 802.15.4 standard. For this standard, devices belonging to the network are categorized into full function devices (FFDs) and reduced function devices (RFDs). FFDs are eligible to be coordinators and are capable of forwarding frames for other members within the network. RFDs lack such capability and rely on FFD's frame forwarding service to communicate with other devices in the WSN. In a ZigBee tree network, the ZC and the ZR nodes are functionally identical to the coordinator nodes, and therefore can only be FFDs. RFDs, on the other hand, must join the tree as ZEDs. To cover enough area for the measurements, the wireless sensor network was designed to integrate one coordinator node to control the network, three router nodes with a bidirectional communication, and fifteen end devices to measure environmental data described in Table I. The WSN was implemented with low-cost elements and open-source technologies that allow large scale implementations. Fig. 2 shows how the coordinator, router and end device nodes are integrated within the WSN.

TABLE I
SENSORS USED FOR THE END DEVICES AND THE ROUTERS IN THE WSN.

Sensor	Measured variable
DHT22	Temperature in Celsius
DHT22	Relative humidity (%)
Flame sensor	Wavelength (mm)
MQ-2	Gas concentration (ppm)
MQ-9	Gas concentration (ppm)

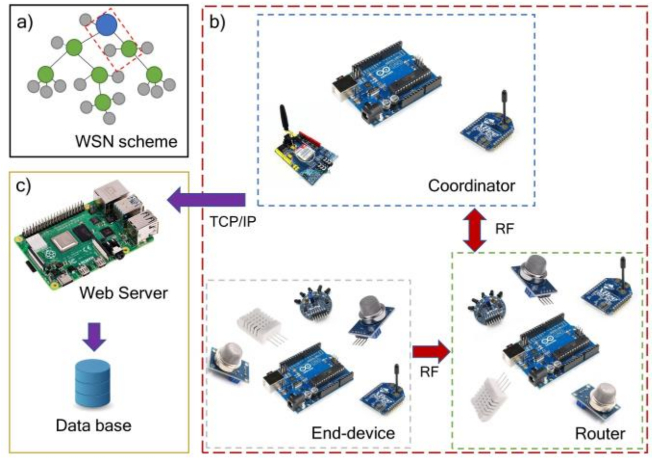

Fig. 2. Components of the implemented architecture. (a) Schematic of a tree-like topology of a WSN. (b) End devices and router nodes incorporate sensors and XBee modules to measure and send data, whereas the coordinator node only includes XBee and GPRS modules for internal and external communication with the server. (c) Web server allocated in a Raspberry Pi embedded system. The server oversees receiving and storing data coming from the WSN.

As shown in Fig. 2, each router and end device were composed of a programmable Arduino UNO board which integrates a DHT22 temperature and humidity sensor, MQ-2 and MQ-9 gas sensors, an infrared wave intensity sensor, and a dedicated XBee to enable the communication with other nodes. The coordinator node incorporated an XBee module to receive the information from the routers and end devices, and a GPRS module that allowed the communication of the wireless sensor network with the Internet. The function of the GPRS SIM900A module was to provide a way to send data measured by the WSN through TCP/IP protocol to a web server [25] (refer to Fig. 2c), which hosted a database and a web service for storing and displaying data in real-time, respectively. A summary of the sensors used for the end devices and router for the proposed architecture, and the measured variables by the WSN are also presented in Table I.

The DHT22 sensor measured the temperature in Celsius and the relative humidity in terms of a percentage rate. The flame sensor provided a binary value depending on the detection of a flame by measuring the electromagnetic wavelength in millimeters. The MQ-9 and MQ-2 sensors measured the concentration of gasses in parts per million (ppm). The values retrieved by the gas sensors were later processed in the web server and turned into a particular gas such as CH_4, CO, or smoke by using the relationship found in the data sheet of each sensor. The Arduino UNO board was used due to its simplicity and easy implementation. The board was programmed to process the data collected by the sensors and send the information to the coordinator and to web server as the destination. Table II summarizes the devices used for each of the components of the wireless sensor network (shown in Fig. 2) implemented in this work.

TABLE II
COMPONENTS OF THE WIRELESS SENSOR NETWORK.

Element	Device
Server	Raspberry Pi 4 with NodeJS server
Coordinator	Arduino + XBee + GPRS module
Router	Arduino + XBee + sensors
End-device	Arduino + XBee + sensors

B. *Web server*

A web server is a computer able to process and store data on a database and listen to and reply to requests through HTTP or HTTPS protocols. In this work, a Raspberry Pi 4 embedded system was used as a local server to receive and store data collected from the WSN. The web server was based on the NodeJS framework, using the JavaScript programming language on the back end. The use of JavaScript on the server-side allowed to improve the response and processing time for each of the requests sent to the web server by using web sockets. The database manager used on the Raspberry Pi was MongoDB and JSON format files to handle the database entries. To configurate the web server, it was necessary to set up the local IP of the device as static and create a domain name system (DNS) to make the server accessible through the Internet. Additionally, it was required to open ports 80 and 443 to enable communication using HTTP and HTTPS protocols, respectively. Ports 3000 and 8080 were also opened for database management and data reception from the wireless sensor network. The web server implemented on the Raspberry Pi carried out the functions of receiving HTTP/HTTPS requests, allocating a web service, storing the collected data, and handling the visualization of data in real-time on a web application constructed using HTML5, CSS and JavaScript languages.

The operation of the fire early-detection system implemented in this work is summarized in the flow chart shown in Fig. 3. First, the acquisition of environmental data is performed by the routers and end devices which process and send the data to the coordinator node using the Zigbee standard. Once the coordinator receives valid data, it processes them to send it over the web server trough a GET request and TCP/IP protocol. On the server-side the data is received and processed. Then, the web server stores the environmental data on the MongoDB database and assists in their real-time visualization on a web client service using web sockets.

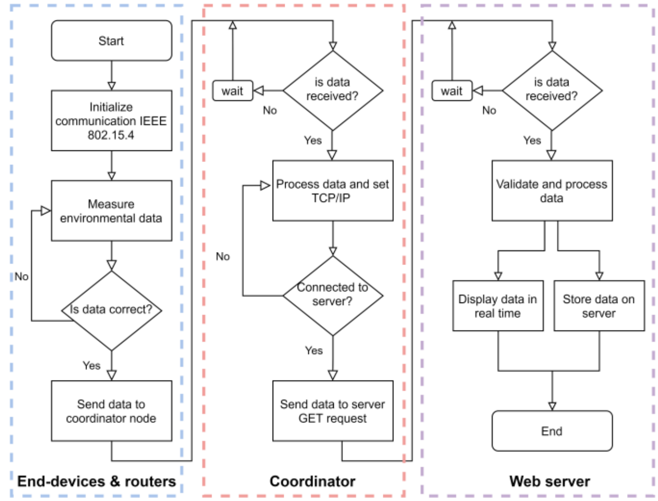

Fig. 3. Flow chart describing the operation of the WSN. Environmental data are collected by the routers and end devices in the WSN and are sent to the coordinator node for processing via Zigbee standard. The coordinator node sends the data to the web server through GET request using TCP/IP protocol. The web server receives the data to process, store and display them in the web application.

III. RESULTS

In this section, we show results regarding time delay and success packet rate obtained from the WSN. Here, the wireless sensor network underwent several tests in order to assess its performance when measuring and sending data. The first experiment consists in measuring the ratio of the number of packets successfully received on the server over the total number of packets sent by the source (end device for this experiment). In this experiment, environmental variables are measured by an end device, and received on the web server (Raspberry Pi). The Arduino UNO used as the end device (refer to Fig. 2) is programmed to encode the measured data into a string to be sent to the coordinator node using the IEEE Zigbee standard. The coordinator node receives the data from the end device and create a new packet containing both data and additional information to perform the GET request to the web server. Each of the packets has a length of 672 bits (or 84 bytes), and has the following structure:

GET /data?node=xx&temp=xx.x&hum=xx&mq2=x.xx&
mq9=x.xx&flame=z&time=HHMMSSss&date=ddmmyy

Where each x corresponds to a digit value between zero and nine, and z is a binary digit i.e., $\{0, 1\}$. For each transmitted set of measurements, the time and date shown in the sequence of bits are retrieved from a computer connected to the end device in order to have an accurate measurement for the tests.

The variables listed in the GET request correspond to (1) the node identifier; (2) temperature in Celsius, relative humidity in percentage, MQ-2 and MQ-9 gas data in ppm, and flame signal (binary value) measured by the end device; and (3), the date and time registered for each measurement. All the environmental variables are concatenated in form of a GET request to be sent to the web server through the TCP/IP protocol. For this experiment, in total, five different tests with

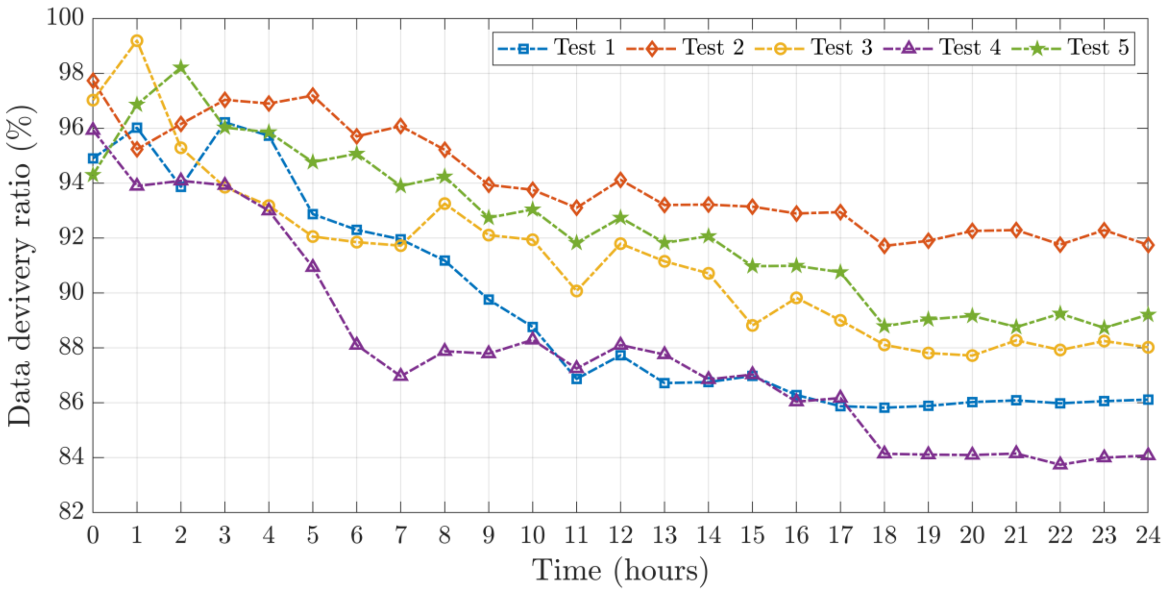

Fig. 4. Measure of data delivery packets for the proposed WSN. For each of the five tests, the average data delivery ratio up to the J^{th} hour is reported.

a duration of 24 hours are performed to test the reliability of the WSN at measuring and transmitting data. During the tests, data are measured and encapsulated on packets and are sent to the server every ten seconds. That is, six packets are sent per minute, 360 per hour and 8,640 per day. Each data packet received at the server is compared with the original data to verify if this is received correctly. Here, the transmission of an i^{th} packet is denoted as $x_i \in \{0,1\}$. $x_i = 1$ if the packet is valid, otherwise $x_i = 0$. The status of N data packets sent for one hour are averaged as shown in (1).

$$\bar{X}_J = \frac{1}{N}\sum_{i=1}^{N} x_i \quad (1)$$

Where N is the number of data packets transmitted up to the j^{th} hour, x_i corresponds to the status of each of the i^{th} data packets sent every ten seconds, and $\bar{X}_J$ is the average calculated up to the j^{th} hour, where $j \in [0,24]$. For each test, the average packet ratio delivery $\bar{X}_J$ is reported to verify the operation and effectiveness of the wireless sensor network. Fig. 4 presents the results after the five tests were performed. The packets compared correspond to the variables measured by the wireless sensor network (end device) and the information received from the web server (allocated in the Raspberry Pi).

For all the test cases, the average data delivery ratio in the wireless sensor network stabilizes on a value above 83% as shown in Fig. 4. The decay on the data delivery ratio happens because in (1), the average is computed for the packets sent from the beginning up to the hour where the data are taken.

The second test aims to study the network time delay during transmission of data from end devices to the web server. According to [26], network time delay metric is used to measure the average end-to-end delay of the transmission of data packets which corresponds to the average time between the successful transmission and reception from the source to the receiver. For this experiment, five different tests with 24 hours of duration each, are performed using the same data packets of 672 bits that are used to study the data delivery ratio. Also, each data packet is sent every ten seconds. The collected data are sent from the end device to the coordinator node via radiofrequency using the Zigbee standard. The information received by the coordinator node is processed and later sent to the web server through the TCP/IP protocol using the SIM900A GPRS module. The times are measured using the time provided in the data stream (corresponding to the time of the measurement), and the time when the web server received the data. Fig. 5 presents the results for each of the five tests. In this experiment, the measured times are averaged for each hour using a similar approach than in (1). That is, the average time per hour is given by (2) as,

$$\bar{T}_J = \frac{1}{N}\sum_{i=1}^{N} t_i \quad (2)$$

where $\bar{T}_J$ is the average time delay during the j^{th} hour, where $j \in [0,24]$, t_i is the time delay for sending the i^{th} data packet, and N is the number of packets sent in the j^{th} hour ($N = 360$).

In general, the WSN shows consistent time delays less than 500 ms for all the five tests performed, as depicted in Fig. 5. Additionally, Table III presents the average of data delivery ratio and time delay measured from the WSN over the 24 hours period for the five tests.

TABLE III
AVERAGE DATA DELIVERY RATIO AND TIME DELAY OF THE WSN (24 HOURS).

Test No.	Average data delivery ratio (%)	Average time delay (ms)
1	89.309	452.315
2	94.061	482.049
3	91.158	475.770
4	87.933	484.266
5	92.365	468.595

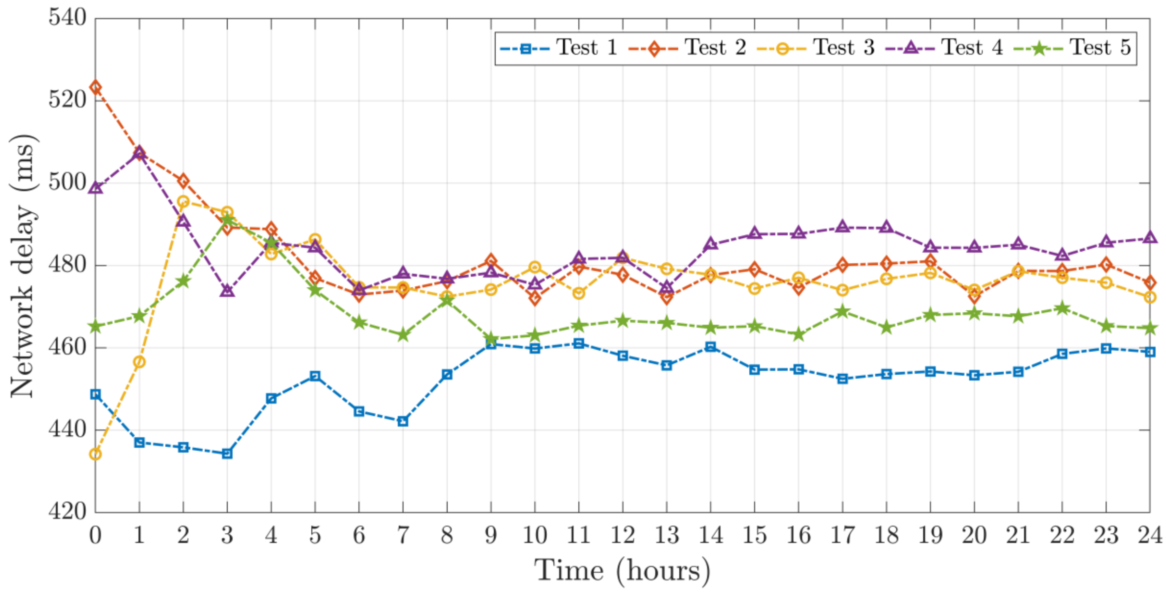

Fig. 5. Measure of network delay in the WSN implemented. For each of the five tests, the average time delay is calculated during the j^{th} hour.

The wireless sensor network exhibits an average data delivery ratio greater than 87.93% in the worst-case scenario during the 24 hours the test lasted. Similarly, the WSN registers an average time delay less than 484.266 ms in all five tests performed. These results indicate that sending and receiving data can be considered in near real-time for forest fire detection and improves state-of-the-art works [26].

IV. Conclusions

We designed and implemented a fire early-detection system based on a wireless sensor network (WSN). The WSN used the Zigbee standard in a tree-like topology configuration for communication between nodes and data transmission of temperature, humidity, flame signal, and gas concentration. The WSN processed and sent the collected data to a web server to properly store and display data on a web service. The WSN was implemented using low-cost and open-access technologies allowing for large-scale deployments. The WSN showed good performance for both data delivery ratio and time delay for different tests that accounted for transmission and reception times. The reported results demonstrate the potential of the network for real-time applications.

A NodeJS server implementing web sockets was built on a Raspberry Pi system to handle real-time data. The web server yielded fast response times while allowed real-time applications. This local server required the configuration and opening of ports 80 and 443 to enable communication using HTTP and HTTPS protocols with the WSN.

The performance of the WSN was evaluated by measuring the error rate and time delay of the system from the moment of collecting data to the time the webserver receives the packets. Results showed that the time delay remains below 484 ms allowing the network to deliver data in near real-time. On the other hand, the average ratio of successfully delivered data packets was over 86% after 24 hours of transmission, suggesting that the proposed WSN outperforms other state-of-the-art implementations.

We evaluated the processing capacity of Raspberry Pi to work as a web server system for the reception and visualization of data received from the Internet through TCP/IP protocol. The server implemented on the Raspberry Pi proved to be reliable for real-time applications, obtaining a good performance regarding the time to process data collected by the WSN prototype. The web server provided nearly real-time reports about the environmental variables on a web service implemented for the early detection of forest fires.

The environmental data collected by the WSN were stored in a local database based on MongoDB. The web service was implemented using open-source frameworks. All the resources and tools used to implement the proposed WSN (such as compilers, APIs, and software tools) are freely accessible. In other words, no type of license was required to develop and deploy the application, allowing it to be a very low-cost service for its implementation and maintenance.

Using Raspberry Pi to host a web service permits the project to be scalable by implementing clusters to create a private cloud space to access the stored data. In addition, web servers implemented in Raspberry Pi help reduce the maintenance and implementation costs of WSN systems.

Acknowledgment

The authors thank Colciencias for partially funding this project by the award of "Jóvenes investigadores e innovadores" 2018. Also, we thank the Universidad Francisco de Paula Santander for funding under the FINU contract 063-2019.

REFERENCES

[1] M. Roelfsema *et al.*, "Taking stock of national climate policies to evaluate implementation of the Paris Agreement," *Nat. Commun.*, vol. 11, no. 1, p. 2096, Dec. 2020, DOI: 10.1038/s41467-020-15414-6.

[2] NOAA National Centers for Environmental Information, "State of the Climate: Global Climate Report for Annual 2020," 2021. [Online]. Available: https://www.ncdc.noaa.gov/sotc/global/202013.

[3] S. Gupta, A. Roy, D. Bhavsar, R. Kala, S. Singh, and A. S. Kumar, "Forest Fire Burnt Area Assessment in the Biodiversity Rich Regions Using Geospatial Technology: Uttarakhand Forest Fire Event 2016," *J. Indian Soc. Remote Sens.*, vol. 46, no. 6, pp. 945–955, Jun. 2018, DOI: 10.1007/s12524-018-0757-3.

[4] J. A. Castro Correa, S. B. Sepúlveda Mora, B. Medina Delgado, and D. Guevara Ibarra, "Servicio web para la geolocalización de los vehículos de transporte público en la ciudad de Cúcuta," *Respuestas*, vol. 23, no. S1, pp. 29–37, Jul. 2018, DOI: 10.22463/0122820X.1498.

[5] S. Li, L. Da Xu, and S. Zhao, "5G Internet of Things: A survey," *J. Ind. Inf. Integr.*, vol. 10, pp. 1–9, Jun. 2018, DOI: 10.1016/j.jii.2018.01.005.

[6] J. S. Rueda and J. M. Talavera Portocarrero, "Similitudes y diferencias entre Redes de Sensores Inalámbricas e Internet de las Cosas: Hacia una postura clarificadora," *Rev. Colomb. Comput.*, vol. 18, no. 2, pp. 58–74, Dec. 2017, DOI: 10.29375/25392115.3218.

[7] J. H. Nord, A. Koohang, and J. Paliszkiewicz, "The Internet of Things: Review and theoretical framework," *Expert Syst. Appl.*, vol. 133, pp. 97–108, Nov. 2019, DOI: 10.1016/j.eswa.2019.05.014.

[8] P. Cardullo and R. Kitchin, "Smart urbanism and smart citizenship: The neoliberal logic of 'citizen-focused' smart cities in Europe," *Environ. Plan. C Polit. Sp.*, vol. 37, no. 5, pp. 813–830, Aug. 2019, DOI: 10.1177/0263774X18806508.

[9] M. Husár, V. Ondrejička, and S. C. Varış, "Smart Cities and the Idea of Smartness in Urban Development – A Critical Review," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 245, no. 8, p. 082008, Oct. 2017, DOI: 10.1088/1757-899X/245/8/082008.

[10] V. Dubey, P. Kumar, and N. Chauhan, "Forest Fire Detection System Using IoT and Artificial Neural Network," in *International Conference on Innovative Computing and Communications*, 2019, pp. 323–337.

[11] J. Granda Cantuna, D. Bastidas, S. Solorzano, and J.-M. Clairand, "Design and implementation of a Wireless Sensor Network to detect forest fires," in *2017 Fourth International Conference on eDemocracy & eGovernment (ICEDEG)*, Apr. 2017, pp. 15–21, DOI: 10.1109/ICEDEG.2017.7962508.

[12] R. Sharma, S. Prakash, and P. Roy, "Methodology, Applications, and Challenges of WSN-IoT," in *2020 International Conference on Electrical and Electronics Engineering (ICE3)*, Feb. 2020, pp. 502–507, DOI: 10.1109/ICE348803.2020.9122891.

[13] A. D. Salman, O. I. Khalaf, and G. M. Abdulsaheb, "An adaptive intelligent alarm system for wireless sensor network," *Indones. J. Electr. Eng. Comput. Sci.*, vol. 15, no. 1, p. 142, Jul. 2019, DOI: 10.11591/ijeecs.v15.i1.pp142-147.

[14] Y. Liu, Y. Liu, H. Xu, and K. L. Teo, "Forest fire monitoring, detection and decision making systems by wireless sensor network," in *2018 Chinese Control And Decision Conference (CCDC)*, Jun. 2018, pp. 5482–5486, DOI: 10.1109/CCDC.2018.8408086.

[15] R. E. Mohamed, A. I. Saleh, M. Abdelrazzak, and A. S. Samra, "Survey on Wireless Sensor Network Applications and Energy Efficient Routing Protocols," *Wirel. Pers. Commun.*, vol. 101, no. 2, pp. 1019–1055, Jul. 2018, DOI: 10.1007/s11277-018-5747-9.

[16] B. Kadri, B. Bouyeddou, and D. Moussaoui, "Early Fire Detection System Using Wireless Sensor Networks," in *2018 International Conference on Applied Smart Systems (ICASS)*, Nov. 2018, pp. 1–4, DOI: 10.1109/ICASS.2018.8651977.

[17] L. Shkurti, X. Bajrami, E. Canhasi, B. Limani, S. Krrabaj, and A. Hulaj, "Development of ambient environmental monitoring system through wireless sensor network (WSN) using NodeMCU and 'WSN monitoring,'" in *2017 6th Mediterranean Conference on Embedded Computing (MECO)*, Jun. 2017, pp. 1–5, DOI: 10.1109/MECO.2017.7977235.

[18] P. K. Singh and A. Sharma, "An insight to forest fire detection techniques using wireless sensor networks," in *2017 4th International Conference on Signal Processing, Computing and Control (ISPCC)*, Sep. 2017, pp. 647–653, DOI: 10.1109/ISPCC.2017.8269757.

[19] S. Abdullah, S. Bertalan, S. Masar, A. Coskun, and I. Kale, "A wireless sensor network for early forest fire detection and monitoring as a decision factor in the context of a complex integrated emergency response system," in *2017 IEEE Workshop on Environmental, Energy, and Structural Monitoring Systems (EESMS)*, Jul. 2017, pp. 1–5, DOI: 10.1109/EESMS.2017.8052688.

[20] S. Gupta and L. Doshi, "An Acknowledgement Based System for Forest Fire Detection via Leach Algorithm," in *2017 3rd International Conference on Computational Intelligence and Networks (CINE)*, Oct. 2017, pp. 17–21, DOI: 10.1109/CINE.2017.16.

[21] J. M. Celis-Peñaranda, C. D. Escobar-Amado, S. B. Sepúlveda-Mora, S. A. Castro-Casadiego, B. Medina-Delgado, and D. Guevara-Ibarra, "Design of a Wireless Sensor Network for Optimal Deployment of Sensor Nodes in a Cocoa Crop," *TecnoLógicas*, vol. 23, no. 47, pp. 121–136, Jan. 2020, DOI: 10.22430/22565337.1361.

[22] C. D. Escobar-Amado, J. M. Celis-Peñaranda, S. B. Sepúlveda-Mora, S. A. Castro-Casadiego, B. Medina-Delgado, and D. Guevara-Ibarra, "Adaptive nodes algorithm to solve the orphan nodes problem in a ZigBee Tree WSN," *Ingeniare. Rev. Chil. Ing.*, vol. 29, no. 2, pp. 285–296, 2021, [Online]. Available: https://www.ingeniare.cl/index.php?option=com_ingeniare&view=d&doc=109/08-ESCOBAR_V.-29-2_3.pdf&aid=853&vid=109&lang=es.

[23] W. Lei and D. Zhiqiang, "Modeling and simulation of forest fire detection and fire spread," in *2017 2nd International Conference on Advanced Robotics and Mechatronics (ICARM)*, Aug. 2017, pp. 65–69, DOI: 10.1109/ICARM.2017.8273136.

[24] O. Y. Monroy-García, D. C. Rolón-Quintero, and S. B. Sepúlveda-Mora, "Sistema Inalámbrico Modular de Bajo Costo para Supervisar Variables Ambientales en Invernaderos: Un Respaldo al Agricultor de Pequeña Escala - Low-Cost Modular Wireless System to Monitor Greenhouse Environmental Variables: A Small-Scale Farmer Support," *Rev. Científica*, vol. 2, no. 29, p. 149, May 2017, DOI: 10.14483//udistrital.jour.RC.2017.29.a5.

[25] S. B. Sepulveda Mora, J. A. Castro Correa, B. Medina Delgado, D. Guevara Ibarra, and O. A. Lopez Bustamente, "Sistema de Geolocalización de Vehículos a través de la red GSM/GPRS y tecnología Arduino," *Rev. EIA*, vol. 16, no. 31, pp. 145–157, Jan. 2019, DOI: 10.24050/reia.v16i31.1269.

[26] L. Alazzawi and A. Elkateeb, "Performance Evaluation of the WSN Routing Protocols Scalability," *J. Comput. Syst. Networks, Commun.*, vol. 2008, pp. 1–9, 2008, DOI: 10.1155/2008/481046.

Jhon Alejandro Castro Correa was born in Villavicencio, Colombia in 1995. He received his bachelor's in Electronics Engineering in 2018 from Francisco de Paula Santander University in Cucuta, Colombia. He served as a junior researcher at the Telecommunications (GIDET) Research, under the award 812-2018 from Colciencias in Colombia. He is currently a M.Sc. and Ph.D. candidate in the Electrical and Computer Engineering department at the Ocean Acoustics laboratory from the University of Delaware. His research interests cover ocean acoustics, machine learning, wireless sensor networks and graph signal processing.
ORCID: https://orcid.org/0000-0002-2507-3535

Sergio Basilio Sepúlveda Mora was born in Cúcuta, Colombia in 1984. He received a bachelor's degree in Electronics Engineering in 2007 from Francisco de Paula Santander University in Cucuta, Colombia. He received his Master of Science in Electrical and Computer Engineering in 2012 from University of Delaware, Newark, DE, USA. He is currently pursuing a Ph.D. in Electrical Engineering at the Institute of Energy Conversion from University of Delaware.

He is an Assistant Professor in the Department of Electricity & Electronics at Francisco de Paula Santander, where he is also a member of the Applied Microelectronics (GIDMA) and Telecommunications (GIDET) Research groups. His research interests include photovoltaic solar energy, microelectronics, wireless sensor networks, data science, and machine learning.
ORCID: https://orcid.org/0000-0002-1248-7616

Byron Medina Delgado was born in Cúcuta, Colombia in 1979. He received a bachelor's degree in Electronics Engineering in 2003 from Francisco de Paula Santander University in Cucuta, Colombia. He received his Master in Electronics Engineering in 2009 from Nacional Experimental del Táchira University, San Cristóbal, Venezuela. He received his Doctor of Science in 2019 from Rafael Belloso Chacín University, Maracaibo, Venezuela. He is an Associated Professor in the Department of Electricity & Electronics at Francisco de Paula Santander, where he is also a member of the Research and Development Group in Electronics and Telecommunications (GIDET). His research interests include, wireless sensor networks, electromagnetic theory, technology transfer and engineering education.
ORCID: https://orcid.org/0000-0003-0754-8629

Christian David Escobar Amado received his Bachelor of Science in Electronics Engineering, from the Francisco de Paula Santander University at Cucuta, Colombia, in 2016. From 2017 to 2018, he worked as a Junior Researcher under the administrative department of science, technology, and Innovation, also known as Colciencias, in Colombia. He is currently a Ph.D. student in Electrical and Computer Engineering at the University of Delaware at Newark, DE, USA, since 2019. As a research assistant, he works on Bayesian optimization methods and deep learning techniques applied to ocean acoustics.
ORCID: https://orcid.org/0000-0003-2907-7311

Dinael Guevara Ibarra (M'2004–SM'14) Received the B.S. degree in electrical engineer (1989) from Universidad Industrial de Santander, in Bucaramanga, Colombia, the M. S. degree in engineering telecommunications (2006) from Universidad Nacional Experimental Politécnica "Antonio José de Sucre".
ORCID: https://orcid.org/0000-0003-3007-8354