Wireless technologies in IoT projects with distributed computing

Tetiana A. Vakaliuk[1,2,3,4], Oleksandr V. Andreiev[1], Oleksandr F. Dubyna[1], Oksana L. Korenivska[1] and Yevheniya O. Andreieva[1]

[1]*Zhytomyr Polytechnic State University, 103 Chudnivsyka Str., Zhytomyr, 10005, Ukraine*
[2]*Institute for Digitalisation of Education of the NAES of Ukraine, 9 M. Berlynskoho Str., Kyiv, 04060, Ukraine*
[3]*Kryvyi Rih State Pedagogical University, 54 Universytetskyi Ave., Kryvyi Rih, 50086, Ukraine*
[4]*Academy of Cognitive and Natural Sciences, 54 Universytetskyi Ave., Kryvyi Rih, 50086, Ukraine*

Abstract
When it comes to creating projects based on the use of the Internet of Things (IoT), wireless sensor networks are often used. The use of edge computing in IoT technology allows reducing system response delays to sensor output signals and increasing the network throughput. At the same time, a short-range sensor network can work locally without access to the Internet, while long-range networks, as a rule, require access to the Internet and use both edge and cloud computing. The article analyzes the possible options for wireless data transmission during the implementation of both short- and long-range IoT projects. Specific examples show the possibility of data transmission over a short distance using ESP-NOW technology, nRF24L01 radio modules and the creation of a local Wi-Fi access point. The range of sensor data transmission between microcontrollers is practically determined for each proposed option. The calculation of the range of the LoRa radio line is carried out for the real sensitivity values of the RFM95W receiver. The use of the Okamura-Hata radio wave propagation model is proposed in order to estimate the total signal loss in the LoRa radio line. The essence of edge computing with the combined use of digital and analog sensors is shown.

Keywords
IoT, wireless sensor network, monitoring system, edge devices

1. Introduction

Nowadays, a large number of projects are based on the use of the Internet of Things (IoT). For example, Sulistyawan et al. [1] describes the design of an IoT parking tracking system based on a NodeMCU ESP8266 microcontroller and an HC-SR04 ultrasonic sensor using a smartphone and a web application. Joshi and Patel [2] offer a smart parking system based on the ESP8266 Wi-Fi module and mobile Internet. In the wireless home automation system project, it is proposed to use the NodeMCU ESP8266 microcontroller to remotely control home appliances and the access system through a web browser and an Android application [3]. As another example, there is smart IoT-based home security system with an ESP32 microcontroller, that takes pictures of the room with a camera and transmits the information to the owner's smartphone when a motion sensor or smoke sensor is triggered. This system is described in [4].

The reliable operation of wireless sensor networks is directly related to the capacity of autonomous power sources of the sensor node. The most energy-consuming operation for sensor nodes is the transmission of data to the wireless environment. Therefore, energy-saving ways of transmission are a key factor in extending the sensors service life, as it is almost entirely dependent on the life of the power battery. Special communication protocols have been developed to solve this problem. To reduce energy consumption, the transmitters of the sensor nodes are usually being turned off, when

doors-2024: 4th Edge Computing Workshop, April 5, 2024, Zhytomyr, Ukraine
tetianavakaliuk@gmail.com (T. A. Vakaliuk); oleks.andreyev@gmail.com (O. V. Andreiev); Dubyna1357@gmail.com (O. F. Dubyna); o.l.korenivska@gmail.com (O. L. Korenivska); Andreyeva.Yevheniya@gmail.com (Y. O. Andreieva)
http://acnsci.org/vakaliuk/ (T. A. Vakaliuk)
0000-0001-6825-4697 (T. A. Vakaliuk); 0000-0002-2601-1491 (O. V. Andreiev); 0000-0003-3448-6072 (O. F. Dubyna); 0000-0002-3735-7690 (O. L. Korenivska); 0009-0006-0822-1176 (Y. O. Andreieva)

no information transfer is required. Thus, only the simplest primary data processing that reduces the amount of transmitted information is performed on the sensor node. Therefore, preliminary processing of measurements is carried out during conducting edge computing. For example, when using analog sensors, the primary electrical signal is subject to analog-to-digital conversion, which can be performed directly in the microcontroller, if it has appropriate inputs for connecting analog signals.

To connect PAN (Personal Area Network) and LAN (Local Area Network) sensors to the global network, it is required to have a connection to a gateway, which can be implemented using technologies such as Ethernet, Wi-Fi and LoRaWAN. Recently, the use of global wireless networks, such as GSM, GPRS and LTE, has become widely used. These networks provide data transmission from sensors to remote cloud resources without the use of gateways. However, the literature research shows that insufficient attention has been paid to the analysis of data transfer options depending on the type of computation used to organize the IoT sensor network. Therefore, the purpose of this article is analyzing possible options for wireless data transmission in the implementation of IoT projects, both in edge and cloud computing.

2. Theoretical background

Both global and local networks are used to implement IoT projects. Wireless sensor networks (WSN) in which the distance between sensors does not exceed several dozens of meters, belong to wireless personal networks (WPAN).

We will consider the “machine to people” data transfer model in IoT, which is presented in figure 1.

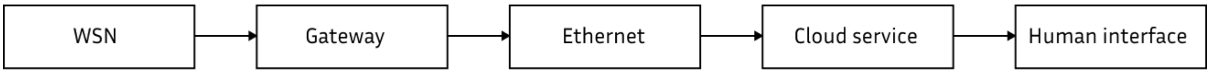

Figure 1: Model of data transmission in IoT.

The protocols that are used to transmit data between the nodes of WSN do not only differ from the protocol of the IoT global network, but also differ significantly from each other. For example, such protocols are ZigBee, Z-Wave and Bluetooth. These standards provide two-way communication between devices. Data is transmitted from the sensors to the network coordinator, which acts as a gateway and provides access to the external network. Through the coordinator, the sensor network also receives external control commands for the actuators that are part of the sensor network nodes. To perform collecting data from sensors and controlling actuators, sensor nodes contain microcontrollers, which must also perform communication functions. The coverage area of WSN can be significantly increased due to the fact that a number of communication protocols implies an opportunity of relaying messages from one sensor network node to another. In this regard, various WSN architectures with sufficiently large number of sensors and actuators with autonomous power are used when implementing IoT projects [5].

The use of cloud services for data storage and processing has lately gained significant development in IoT projects because of the integrated use of the wireless and M2M communications and the global Internet network. GSM, CDMA, LTE, WiMAX cellular networks provide access to the global Internet network with the possibility of using cloud computing. This provides direct communication between the "Internet of Things" and cloud services in wireless networks with a long range [6, 4].

A short-range wireless sensor network uses edge computing to display information within the reach of edge devices [7, 8]. For example, when implementing the project of a home weather station, it is not necessary to require access to the global network. The transmission of temperature and humidity measurement data can be carried out using communication protocols of wireless sensor networks over a short distance. The need for both increasing the throughput of the network and the ability to minimize the delay of transmission and data processing has led to the necessity of using edge computing in software based on IoT technology [9]. Quite a lot of attention is paid to the efficiency of data transmission using Wi-Fi technology in IoT projects. For example, in [7] “delays, loss of packets depending on their size, the ratio of service information to useful information in one transaction during data transmission using the MQTT and CoAP protocols are determined", and in [10] "the possibility of network overload situations and reducing its throughput is analyzed".

The maximum distance over which data packets can be transmitted between wireless sensor network nodes depends on many factors. To organize communication, first of all, it is necessary to choose the frequency range of the radio line. Nowadays, ZigBee, Z-Wave, Bluetooth, Wi-Fi and LoRaWAN standards, which use ISM frequency bands, are widely used to create IoT projects. The ISM band is available license-free in most countries, under the condition of limited transmitter's output power level. Changing the communication range is possible by changing both the sensitivity of the receiving device and by choosing the type and height of the antenna systems. At the same time, the communication range depends on the loss of the useful signal during propagation from the transmitter to the receiver. Bluetooth wireless technology is widely used, when it comes to creating home automation projects with the transmission of sensor data and control of devices at a short distance. This standard uses a frequency of 2.4 GHz and provides economical consumption of autonomous power sources [5].

It is convenient to use the nRF24L01 transceiver to create a wireless sensor network. It provides software selection of one of 125 ISM frequency channels in the 2.4-2.525 GHz range and has a printed antenna with a gain of 2 dBi. One receiver with a sensitivity of -82dBm and six transmitters can work simultaneously on the frequency of one channel. The transmitter power level is programmable from -18dBm to 0dBm in 6dBm increments. GFSK modulation of the frequency of the selected channel is used for data transmission. The SPI interface is used to connect the nRF24L01 to the microcontroller [11].

A gateway is used to get remote control of sensor network devices. The gateway is a central point of communication for all devices that work according to a certain protocol. It connects to the home Wi-Fi network. At the same time, home automation devices responsible for security, lighting, climate, etc. are connected to the gateway. As a result of the application of edge data computing from smart devices in the house, the Wi-Fi channel is not overloaded, and the response delay to the event is reduced compared to the use of cloud services. Sometimes Wi-Fi response delays can reach up to ten seconds [7].

Often there is a need to organize a gateway for access to the global Internet network several kilometers away from the sensor network. In this case, the LoRaWAN network protocol can be used for data transmission. This protocol has low energy consumption and uses LoRa broadband modulation at the physical level. The LoRa physical radio interface uses broadband radio signals with a big base B. This signal is highly resistant to interference. A CSS radio signal with bandwidth $BW = 125$, 250 or 500 kHz is used for data transmission. During digital data transmission, the radio signal base $B = BW \cdot T_{sym}$ is adaptively changed to ensure the required communication quality. This is achieved by changing the duration of the symbol $T_{sym} = 2^{SF}/BW$, which depends on the spreading factor of the radio signal (SF). This coefficient determines the data bits quantity transmitted during the time T_{sym} [12]. The LoRaWAN network protocol, in addition to the adaptive change in data transmission speed, also provides for changing the transmitter power for each edge device individually to ensure the specified quality of data transmission and economical use of autonomous power sources. At the same time, the radio range also changes.

The method of determining the maximum possible distance between WSN nodes involves the development of a distance calculation method or practical distance determination during the implementation of IoT projects. Therefore, when building a sensor network using a LoRa physical interface, it is important to have a method for calculating the range of transmission of data packets at a certain speed.

The maximum communication range R will be achieved under the condition that the power level of the received signal P_S is equal to the sensitivity of the receiver. The power level of the received signal in the radio line using radio waves of length λ, at the transmitter power level P_T, can be calculated by the formula [13, 14]:

$$P_S = P_T + G_T + G_R - L_{Loss}, \tag{1}$$

where L_{Loss} is signal loss during propagation from the transmitter to the receiver, G_T, G_R are coefficients of transmitting and receiving antennas.

Losses of the useful signal L_{Loss} are determined by specific conditions of radio wave propagation at a distance R. The multi-beam nature of radio waves propagation, the formation of shadow zones, multiple reflection and scattering of radio waves in the urban environment creates the phenomenon of intersymbol interference (ISI) in the transmission of digital data. Signal distortions caused by ISI can cause a deterioration in the quality of digital information transmission. Besides, there are signal losses during propagation in the atmosphere and due to the imperfection of the transceiver. All this leads to additional signal losses. The Okumura-Hata radio wave propagation model is well suited for estimating the total signal loss in the LoRa radio line, according to which the loss in the city is calculated by the expression [13]:

$$L_{50/Town} = 69.55 + 26.16 \lg f_{[MGz]} - 13.83 \lg h_B - a\left(h_M\right) + \left(44.9 - 6.55 \lg h_B\right) \cdot \lg R_{[km]}, \quad (2)$$

where $a\left(h_M\right)$ is correction factor.

For a small and medium-sized city, this coefficient is determined as follows:

$$a\left(h_M\right) = \left(1.11 \lg \left(f_{[MGz]}\right) - 0.7\right) h_M - \left(1.56 \lg \left(f_{[MGz]}\right) - 0.8\right). \quad (3)$$

To determine the signal power level at the receiver input, it is advisable to choose the maximum possible value of the radio signal attenuation.

3. Results

To analyze possible options for wireless data transmission, the authors of this article implemented examples of IoT projects and practically determined the range of sensor data transmission between microcontrollers for each proposed option.

ESP8266 and ESP32 microcontrollers from Espressif Systems are widely used to create IoT projects. They both have a built-in Wi-Fi module. Moreover, the ESP32 microcontroller also supports the Bluetooth standard.

The results of the home weather station project using the ESP32 microcontroller and the DHT11 sensor are shown in figure 2. Data transmission of temperature and humidity measurements was carried out via the Bluetooth interface with display on the mobile device in the “Serial Bluetooth Terminal” application. The interface allows you to organize a home automation system to integrate or control electrical and electronic devices in the house at low cost. For instance, in the home weather station project, measurement data were displayed on the screen upon request sent to the microcontroller from the mobile application. The maximum range of communication between devices in the room was up to 30 meters.

The authors also implemented a project for transmitting temperature and humidity measurements using a DHT11 sensor between two nRF24L01 transceivers under the control of ESP8266 microcontrollers. The digital measurements data were analyzed both on the transmitting and receiving sides. As shown in figure 3, data transmission over the radio line is synchronous and error-free. It was practically determined that the range of communication is provided up to 30 m indoors and up to 100 m in the open area.

When using ESP8266 and ESP32 microcontrollers, it is also possible to create a local Wi-Fi access point with the display of sensor data on a webpage. The access to this webpage can be gained using any device, a laptop for example. The temperature and humidity measurement results can be displayed on a webpage using an IP address or DNS. This is shown in figure 4. Connection to the local Wi-Fi access point was carried out at a distance of at least 100 m. Using nRF24L01 transceivers allows to increase distance of measurement data transmission up to 200 m.

A home automation system of any standard can work completely locally without access to the Internet, which eliminates delays in the response of smart devices to events. For example, this is very important for motion sensors that should turn on the light after detecting a person.

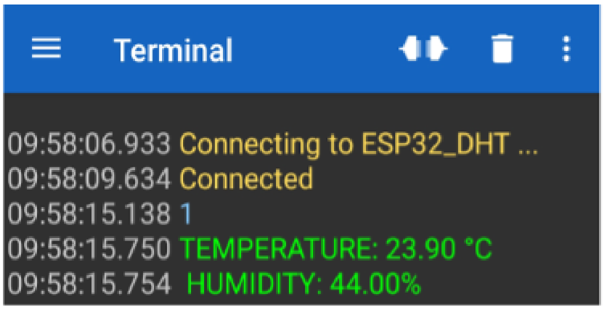

Figure 2: Transmission of measurements via the Bluetooth interface.

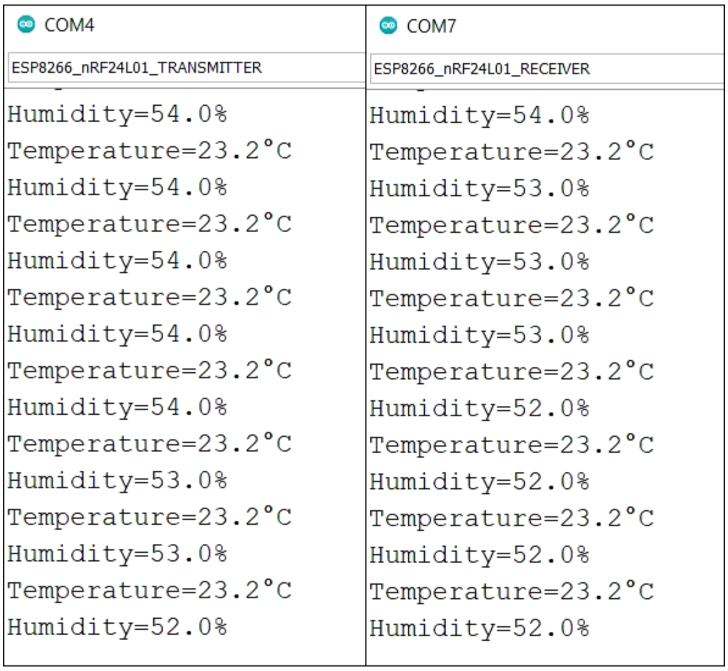

Figure 3: Transfer of temperature and humidity measurements between two transceivers nRF24L01.

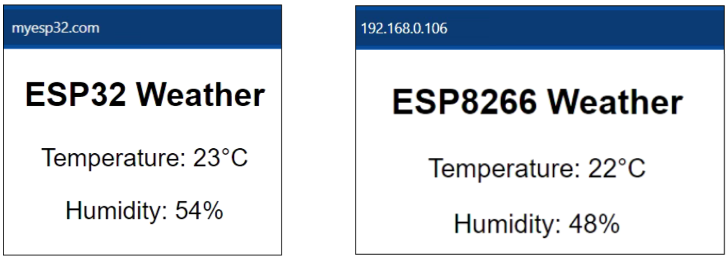

Figure 4: Display of temperature and humidity measurements on a webpage.

ESP-NOW technology, developed by Espressif Systems, can also be used for two-way forwarding of data packets of up to 250 bytes with a transmission speed of no more than 1 Mbit/s between controllers. This technology is based on a simplified Wi-Fi protocol. At the same time, it is possible to organize a WSN in which communication between no more than 20 pairs of devices will be maintained, with the transmitter being informed about the success of forwarding packets. In order to send messages, you need to know the unique MAC address of the boards. If you need to collect data from several boards onto one, for example, to display data from several sensors on a web server, you can use the "one-slave – multiple-master" configuration. It is also possible to create a "one-master – multiple-slaves" configuration, when one board sends commands to different boards of microcontrollers of the ESP series [15].

The results of distance measurement transmission between ESP32 controllers using ESP-NOW technology are shown in figure 5. The distance was measured by an ultrasonic sensor HC-SR04. The distance in centimeters was calculated on the edge device. Received data were displayed on the laptop screen. During the practical implementation of the project, it was determined that the range of data transmission is up to 100 m.

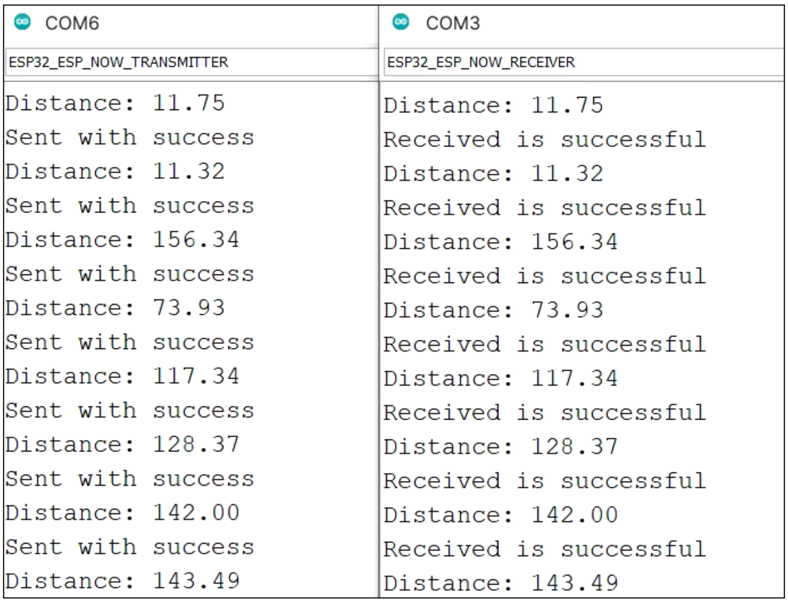

Figure 5: Ultrasonic distance meter using technology ESP-NOW.

Transmission of sensor data to a server, cloud service or edge user can be done through a gateway based on ESP32 or ESP8266 microcontrollers. For instance, the authors of the article created a gateway with a connection to the Wi-Fi access point based on the ESP8266 microcontroller. Measurements data from indoor air quality control sensors were transferred to this gateway using nRF24L01 transceivers. Afterwards, those measurement results were displayed at the ThingSpeak cloud service. A DHT11 digital sensor was used to measure temperature and humidity. An MQ-2 analog sensor was used to determine the concentration of hydrocarbon gases. The edge computing of measurement data was carried out in the ESP8266 microcontroller of the transmission part of the radio line. In order to read digital data from the DHT11 sensor, a library supporting the SDA interface was used. The gas concentration was determined by the voltage at the output of the MQ-2 sensor. The built-in 10-bit ADC of the ESP8266 board was used to get digital measurement data of output voltage. The relative internal resistance of the sensor was calculated based on the measured voltage.

This resistance value was used to estimate the gas concentration value based on the calibration characteristic of the sensor. The gas concentration value was sent to the nRF24L01 transceiver through the SPI interface. At the receiving end of the radio line, from the output of another nRF24L01transciever, the gas concentration value was input to the ESP8266 microcontroller via the SPI interface. On the same controller, a gateway was created for transmitting gas concentration measurements to the ThingSpeak by connecting to a Wi-Fi access point. The change in measurements of air quality control sensors at a certain time interval, which was output to the ThingSpeak cloud service, is shown in figure 6.

It should be noted, that the MQ-2 sensor does not determine the type of gas. It only reacts to an increase in the concentration of liquefied gas and other carbohydrates in the air. To simulate an increase in LPG content in the air, a gas lighter refill aerosol can was used. Figure 6 shows that the sensor responds very well to an increase in the concentration of this gas. Blowing on the sensor also leads to an increase in CO concentration. In addition, a simultaneous increase in temperature and air humidity according to the measurements of the DHT11 sensor was also noted.

Therefore, the graphical display of changes in controlled parameters in the IoT cloud service ThingS-

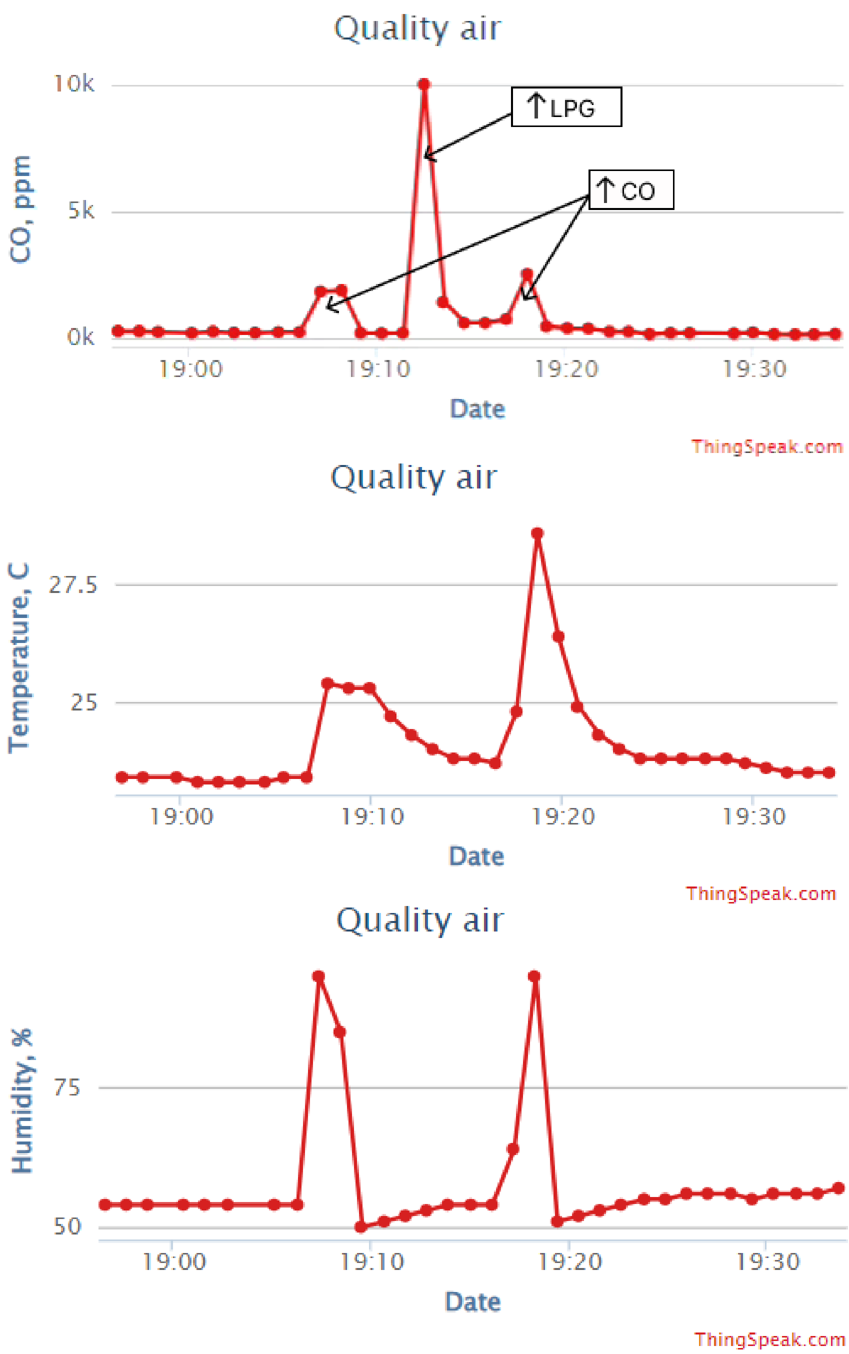

Figure 6: Display of measurements of air quality control sensors in the cloud service ThingSpeak.

peak allows you to carry out both daily monitoring of changes in parameters and statistical analysis of measurements. However, a necessary condition for the correct operation of this service is the implementation of a delay of at least 20 seconds between the transmission of measurements of each channel [16]. An attempt to reduce the delay time or to eliminate it at all, led to a disruption of the service. In order to display the dynamic change of the controlled parameter, the authors developed an IOT project for measuring CO concentration in the room using the Blynk cloud service. The display of CO concentration in Blynk.Console is shown in figure 7.

In order to determine the coverage area of a wireless sensor network using the LoRaWAN communication protocol, the range of data transmission over the LoRa radio line at a specified speed was calculated. The range of data transmission over the LoRa radio link is determined by the selected uplink (UL) and downlink (DL) parameters. These parameters in Europe are shown in table 1.

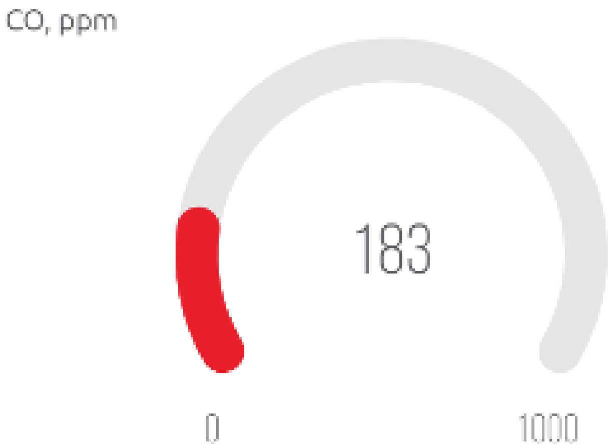

Figure 7: Display of measurements of the MQ-2 sensor in the "Blynk" cloud service.

Table 1
Parameters of the LoRa standard in Europe.

Parameter	Band1, MHz	BW UL, kHz	BW DL, kHz	P_T UL, dBm	P_T DL, dBm	SF	Modulation
Value	863 – 870	125/250	125	2-14	14	7-12	LORA, GFSK, MSK

Typical values of LoRa modem parameters for the frequency of 868 MHz are given in table 2[17].

Table 2
Example LoRaTM modem performances, 868 MHz.

Bandwidth (kHz)	Spreading Factor	Coding rate	Nominal Rb (bps)	Sensitivity indication (dBm)
125	6	4/5	9380	-118
125	12	4/5	293	-136

The approximate communication range R and the data transmission rate R_b, which is provided by a LoRa radio line operating at a frequency of 868 MHz and $BW = 125$ kHz were calculated. The omnidirectional antenna and the transmitters with a power level of 14 dBm were used for conducting the calculations. The communication range according to expressions (1)-(3), under the condition that $h_B = 30$ m and $h_M = 2$ m, was calculated. The speed of information transmission without an interference-resistant code ($CR = 1$) is defined by the expression $R_b = SF \cdot BW/2^{SF}$. The use of an interference-resistant code reduces the speed of information transmission according to the value of the CR parameter. The results of the calculation of the communication range and data transmission speed on the LoRa radio line for the value of $CR = 4/5$ are shown in table 3.

Table 3
The results of calculating the range and speed of data transmission over the LoRa radio line.

SF	6	7	8	9	10	11	12
R,km	3	4,5	5,5	6,7	8,1	8,7	10
R_b, bps	9375	5469	3125	1758	977	537	293

As can be seen from the table 3, increasing the value of SF leads to increase in the communication range with a simultaneous decrease in the information rate of data transmission.

4. Conclusions

The use of edge computing in IoT technology allows reducing system response delays to sensor output signals and increasing the throughput of the network. This type of distributed computing is always carried out in close proximity to the edge devices. Therefore, edge computing takes place in the creation of sensor networks of both short- and long-range. At the same time, a short-range sensor network can work locally without access to the Internet, while long-range networks, as a rule, require access to the Internet and use both edge and cloud computing.

The article analyzes the possible options for wireless data transmission during the implementation of both short- and long-range IoT projects. Using real examples, the authors show the possibility of data transmission over a short distance using ESP-NOW technology, nRF24L01 radio modules and the creation of a local Wi-Fi access point. The results of the home weather station project using Bluetooth technology were presented. The range of sensor data transmission between microcontrollers was practically determined for each proposed option.

The calculation of the range of the LoRa radio line was carried out for the real sensitivity values of the RFM95W receiver. To estimate the total signal loss in the LoRa radio line, the use of the Okamura-Hata radio wave propagation model was proposed. The obtained values of the radio line range make it possible to more accurately determine the WSN coverage area when using the LoRaWAN communication protocol.

The essence of edge computing with the combined use of digital and analog sensors was shown. An example of data transmission of the air quality control system through a gateway based on an ESP8266 microcontroller with a graphical display of measurements in the IoT cloud service ThingSpeak and Blynk was provided.

In further research, it is planned to practically determine the maximum communication range between WSN nodes by implementing IoT projects using RFM95W modems.

5. Author contributions

Conceptualization, formulation of tasks – Tetiana Vakaliuk; air quality control projects, analysis of results – Oksana Korenivska, Oleksandr Dubyna; distance meter project using ESP-NOW technology, analysis of results – Oleksandr Andreiev; conceptual analysis - Tetiana A. Vakaliuk, Oleksandr Andreiev, method of calculating the radio line range, analysis of results – Yevheniya Andreieva; writing – original draft preparation and editing – Tetiana Vakaliuk, Yevheniya Andreieva.

All the authors have read and agreed to the published version of this manuscript.

References

[1] V. N. Sulistyawan, N. A. Salim, F. G. Abas, N. Aulia, Parking Tracking System Using Ultrasonic Sensor HC-SR04 and NODEMCU ESP8266 Based IoT, IOP Conference Series: Earth and Environmental Science 1203 (2023) 012028. doi:10.1088/1755-1315/1203/1/012028.

[2] A. Joshi, J. Patel, Smart parking system using esp8266 wi-fi module, International Journal of Advanced Research in Science Communication and Technology 3 (2023) 88–95. doi:10.48175/IJARSCT-12015.

[3] G. Rajeshkumar, P. Rajesh Kanna, S. Sriram, S. Sadesh, R. Karunamoorthi, P. Mahudapathi, Home Automation System Using Nodemcu (ESP8266), in: R. Buyya, S. Misra, Y.-W. Leung, A. Mondal (Eds.), Proceedings of International Conference on Advanced Communications and Machine Intelligence, Springer Nature, Singapore, 2023, pp. 293–302. doi:10.1007/978-981-99-2768-5_28.

[4] O. L. Korenivska, T. M. Nikitchuk, T. A. Vakaliuk, V. B. Benedytskyi, O. V. Andreiev, IoT monitoring system for microclimate parameters in educational institutions using edge devices, in: T. A. Vakaliuk, S. O. Semerikov (Eds.), Proceedings of the 3rd Edge Computing Workshop, Zhytomyr,

Ukraine, April 7, 2023, volume 3374 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2023, pp. 66–80. URL: https://ceur-ws.org/Vol-3374/paper05.pdf.
[5] A. McEwen, H. Cassimally, Designing the Internet of Things, Wiley, 2014. URL: https://madsg.com/wp-content/uploads/2015/12/Designing_the_Internet_of_Things.pdf.
[6] ETSI TS 102 690 V2.1.1 (2013-10) "Machine-to-Machine communications (M2M); Functional architecture", 2013. URL: https://www.etsi.org/deliver/etsi_ts/102600_102699/102690/02.01.01_60/ts_102690v020101p.pdf.
[7] E. Malokhvii, H. Molchanov, Research of data transmission protocols in the conditions of the Internet of Things, Control, Navigation and Communication Systems. Academic Journal 1 (2022) 66–74. doi:10.26906/SUNZ.2022.1.066.
[8] O. L. Yershova, T. V. Tomashevska, Peripheral Computations: The Basis for Data Processing in Internet of Things, Scientific Bulletin of the National Academy of Statistics, Accounting and Audit (2021) 97–103. doi:10.31767/nasoa.4-2020.11.
[9] O. V. Talaver, T. A. Vakaliuk, Reliable distributed systems: review of modern approaches, Journal of Edge Computing 2 (2023) 84–101. doi:10.55056/jec.586.
[10] N. I. Pravorska, N. V. Hripinska, Development Of Sensor For Internet Of Things Data Transferring, Bulletin of Khmelnytsky National University. Technical sciences 6 (2018) 193–197. doi:10.31891/2307-5732-2018-267-6(2)-193-197.
[11] Single chip 2.4 GHz Transceiver nRF24L01, 2006. URL: https://www.sparkfun.com/datasheets/Components/nRF24L01_prelim_prod_spec_1_2.pdf.
[12] LoRa and LoRaWAN: A Technical Overview, Semtech, 2019. URL: https://lora-developers.semtech.com/uploads/documents/files/LoRa_and_LoRaWAN-A_Tech_Overview-Downloadable.pdf.
[13] A. Pinto-Erazo, L. Suárez-Zambrano, F. Cuzme-Rodríguez, E. Jaramillo-Vinueza, Study Case: LPWAN Propagation Power Estimation in Outdoor Scenarios, Based on the Okumura-Hata Model, in: V. Robles-Bykbaev, J. Mula, G. Reynoso-Meza (Eds.), Intelligent Technologies: Design and Applications for Society, Springer Nature Switzerland, Cham, 2023, pp. 113–123. doi:10.1007/978-3-031-24327-1_10.
[14] T. A. Vakaliuk, O. V. Andreiev, O. F. Dubyna, T. M. Nikitchuk, I. V. Puleko, Detection of the signals of the terrestrial radar stations by spacecraft with a passive synthesis of the antenna aperture, Radio Electronics, Computer Science, Control (2023) 13. doi:10.15588/1607-3274-2023-2-2.
[15] ESP-NOW wireless communication protocol, 2023. URL: https://www.espressif.com/en/solutions/low-power-solutions/esp-now.
[16] ThingSpeak for IoT Projects, 2023. URL: https://thingspeak.com.
[17] SX1276/77/78/79 -137MGz to 1020 MGz Low Power Long Range Transceiver, 2015. URL: https://html.alldatasheet.com/html-pdf/800239/SEMTECH/SX1276/891/3/SX1276.html.