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Use of wireless technologies in IoT projects

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. Edge computing in IoT technology reduces system response delays to sensor output signals and increases 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 paper shows the features of the application of both peripheral and cloud computing in the practical implementation of IoT projects with various methods of wireless data transmission. Specific examples show the possibility of data transmission over a short distance using ESP-NOW technology, nRF24L01 radio modules and creating 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 actual sensitivity values of the receiver. The Okamura-Hata radio wave propagation model is proposed to estimate the LoRa radio line's total loss. The operational range of LoRa modules with different types of signal modulation is practically determined. The essence of edge computing combined with digital and analogue sensors is shown. Peculiarities of peripheral computing during the implementation of IoT projects for remote control of blood saturation of patients using wireless technologies are considered. 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[1].

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

1. Introduction

Nowadays, many projects are based on the Internet of Things (IoT). For example, Sulistyawan et al. [24] 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 [7] offer an intelligent parking system based on the ESP8266 Wi-Fi module and

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[1] This article is an extended version of a conference talk presented at the 4th Edge Computing Workshop (doors 2024) [28]

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)
https://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)

mobile Internet. The wireless home automation system project proposes using the NodeMCU ESP8266 microcontroller to remotely control home appliances and the access system through a web browser and an Android application [19]. Another example is an intelligent 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 [8].

Modern wireless technologies and IoT are also widely used for remote monitoring of the blood saturation of patients with COVID-19 with a mild and moderate degree of disease severity at home. This helps to exclude direct doctor contact with the patients [16]. Therefore, much attention in the literature is devoted to the development of various variants of pulse oximeters, including those using IoT technologies. However, at the same time, it is usually assumed that the control device is constantly placed on the patient's finger. Therefore, almost no attention is paid to the need for feedback control from the patient [15, 20]. At the same time, a number of scientists have explored the possibility of using IoT devices [6, 9] and fuzzy logic [2, 23] to study air quality.

The rapid growth of IoT applications has led to a proliferation of wireless technologies and computing paradigms, each with its own characteristics and performance metrics. However, there is a lack of comprehensive studies that provide practical insights into selecting and implementing these technologies based on the specific requirements of IoT projects. Moreover, the interplay between edge and cloud computing in IoT applications is poorly understood, particularly regarding their impact on system responsiveness, network throughput, and data processing capabilities.

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 data transmission to the wireless environment. Therefore, energy-saving ways of transmission are a critical factor in extending the sensor's service life, as it is almost entirely dependent on the life of the power battery. Particular communication protocols have been developed to solve this problem. To reduce energy consumption, the sensor node transmitters are usually turned off when no information transfer is required. Thus, only the most straightforward primary data processing that reduces the amount of transmitted information is performed on the sensor node. Therefore, preliminary processing of measurements is carried out while conducting edge computing. For example, the primary electrical signal is subject to analogue-to-digital conversion when using analogue sensors. It can be performed directly in the microcontroller with appropriate inputs for connecting analogue signals.

To connect PAN (Personal Area Network) and LAN (Local Area Network) sensors to the global network, a connection to a gateway is required, which can be implemented using technologies such as Ethernet, Wi-Fi, and LoRaWAN. Global wireless networks, such as GSM, GPRS, and LTE, have recently become widely used. These networks provide data transmission from sensors to remote cloud resources without the use of gateways. At the same time, in the articles devoted to developing IoT projects using wireless technologies, a particular technology is proposed without considering the essence of the calculations performed by the nodes of the IoT sensor network.

This paper aims to fill these gaps by providing a detailed analysis of various wireless data transmission methods and their integration with edge and cloud computing in real-world IoT scenarios. By addressing these challenges, we seek to enable practitioners to make informed decisions when designing and deploying IoT solutions.

Therefore, the purpose of this article is twofold:

1. To comprehensively analyse various wireless data transmission methods used in IoT projects, considering both short-range and long-range communication scenarios. By implementing real-world examples, we demonstrate the practical aspects and performance characteristics of technologies such as ESP-NOW, nRF24L01 radio modules, Bluetooth, and local Wi-Fi access points.
2. To investigate the role of edge and cloud computing in IoT projects, showcasing their integration with wireless sensor networks. We highlight the benefits of edge computing in reducing system response delays and increasing network throughput while also exploring the use of cloud services for data storage, processing, and visualisation.

The remainder of this paper is structured as follows: section 2 provides the theoretical background, covering the fundamentals of wireless sensor networks, IoT communication protocols, and edge and cloud computing paradigms. Section 3 presents the results of our study, including the implementation of various IoT projects using different wireless technologies and the integration of edge and cloud computing. In section 4, we discuss our findings, comparing them with existing literature and highlighting the novelty and improvements of our work. Finally, section 5 concludes the paper, summarising the key contributions and outlining future research directions.

2. Theoretical background

Implementing IoT projects requires both global and local networks. 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.

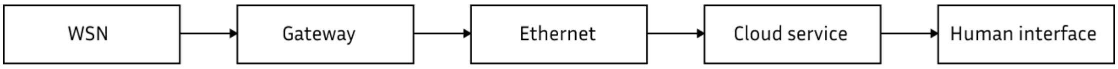


Figure 1: Model of data transmission in IoT.

The protocols used to transmit data between the nodes of WSN differ not only from the protocol of the IoT global network but also 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 collect data from sensors and control actuators, sensor nodes contain microcontrollers, which must also perform communication functions. The coverage area of WSN can be significantly increased because several communication protocols imply an opportunity to relay messages from one sensor network node to another. In this regard, various WSN architectures with a sufficiently large number of sensors and actuators with autonomous power are used when implementing IoT projects [14].

Cloud data storage and processing services have recently developed significantly in IoT projects because of the integrated use of wireless and M2M communications and the global Internet network. GSM, CDMA, LTE, and WiMAX cellular networks provide access to the global Internet network, which can be used for cloud computing. This provides direct communication between the Internet of Things and cloud services in wireless networks with a long-range [4, 8].

A short-range wireless sensor network uses edge computing to display information within the reach of edge devices [13, 31]. 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 network's throughput and minimising the delay of transmission and data processing has led to the necessity of using edge computing in software based on IoT technology [26]. Much attention is paid to data transmission efficiency using Wi-Fi technology in IoT projects. For example, in [13] "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 [18] "the possibility of network overload situations and reducing its throughput is analysed".

The maximum distance 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 a 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 valuable signal during propagation from the transmitter to the receiver. Bluetooth wireless technology is widely used when creating home automation projects that transmit sensor data and control devices at a short distance. This standard uses a frequency of 2.4 GHz and provides economical consumption of autonomous power sources [14].

The choice of wireless technology for a specific IoT application depends on several factors, such as range, data rate, power consumption, and cost. For example, ZigBee is often selected for short-range, low-power, and low-cost applications, such as home automation and industrial control systems. ZigBee's mesh networking capabilities suit scenarios where devices are distributed across a relatively small area and require reliable communication. On the other hand, LoRaWAN is preferred for long-range, low-power, and low-data-rate applications, such as environmental monitoring, asset tracking, and intelligent agriculture. LoRaWAN's ability to cover vast areas with minimal infrastructure makes it an attractive choice for applications that require wide-area coverage and extended battery life. Other technologies, such as Bluetooth and Wi-Fi, are chosen based on their unique characteristics and the specific requirements of the IoT application. By carefully considering these factors, developers can select the most appropriate wireless technology to meet the needs of their IoT projects. Table 1 compares several popular

IoT communication protocols regarding their energy efficiency, range, and data transmission capabilities.

Table 1
Comparison of IoT communication protocols.

Protocol	**Energy efficiency**	**Range**	**Data transmission capabilities**
ZigBee	High	10-100 m	Low (250 kbps)
Bluetooth	Medium	10-100 m	Medium (1-2 Mbps)
Wi-Fi	Low	50-100 m	High (up to 54 Mbps)
LoRaWAN	Very high	2-15 km	Very Low (0.3-50 kbps)
NB-IoT	High	1-10 km	Low (20-250 kbps)
Sigfox	Very high	3-50 km	Very low (100 bps)

As shown in table 1, ZigBee and LoRaWAN offer high energy efficiency, making them suitable for applications that require long battery life. However, their data transmission capabilities are limited compared to other protocols like Wi-Fi and Bluetooth. Wi-Fi provides high data rates but consumes more power, making it less suitable for battery-operated devices. Bluetooth balances energy efficiency and data transmission capabilities, making it a popular choice for short-range IoT applications. NB-IoT and Sigfox are cellular-based protocols that offer long-range communication and high energy efficiency, but their data transmission capabilities are limited. By considering the trade-offs between energy efficiency, range, and data transmission capabilities, developers can select the most appropriate protocol for their specific IoT use case.

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 -82 dBm and six transmitters can work simultaneously on the frequency of one channel. The transmitter power level is programmable from -18 dBm to 0 dBm in 6 dBm 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 [22].

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 specific 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. Wi-Fi response delays can sometimes reach up to ten seconds [13].

Often, there is a need to organize a gateway for access to the global Internet network several kilometres 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 an extensive 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 $B = BW \cdot T_{sym}$ adaptively changes 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 essential to have a method for calculating the transmission range of data packets at a certain speed.

The maximum communication range R will be achieved when the power level of the received signal P_S is equal to the receiver's sensitivity. 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 [17, 28, 29]:

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

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 valuable signal L_{Loss} are determined by specific radio wave propagation conditions at a distance R. The multi-beam nature of radio wave propagation, the formation of shadow zones, and multiple reflections and scattering of radio waves in the urban environment create intersymbol interference (ISI) in digital data transmission. 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 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 [17]:

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

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

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

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

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

The pulse oximeter, one of the sensors monitoring vital health indicators, is at the lowest level in the general architecture based on IoT cloud technologies. The pulse oximeter's operation principle is that the device emits fluctuations of red and infrared wavelength and measures the amount of light reflected from the skin's capillaries. This amount depends on the composition of the arterial blood and the amount of oxidized haemoglobin. The pulse oximeter measurement result shows blood oxygen saturation (SpO2) as a percentage. The average blood saturation index of a healthy person should exceed 96%. Its decrease by 3-4% indicates a severe disease [16]. In most models of this device, the pulse oximeter sensor is attached to the finger. The development of a portable pulse oximeter with the MAX30102 sensor is connected to the Arduino platform through the I2C interface, where the measurements are processed with the results displayed on the external TFT screen. IoT technologies make it possible to remotely monitor the results of patients' blood saturation measurements and display them on cloud services. For example, in [20], it is proposed to implement an IoT pulse oximeter based on the ESP32 platform, which, due to the built-in Wi-Fi module, makes it possible to transfer measurement data of the MAX30100 sensor via the Internet to the ThingSpeak cloud service and display it in the form of graphical dependencies over a sufficiently long time interval. The personal physician periodically monitors this data by accessing the cloud service ThingSpeak, which helps to display it on a smartphone, tablet or personal computer.

Calculation of the value of blood saturation based on the results of sensor measurements is carried out using the ratio [15]:

$$R = \frac{AC_{Red}/DC_{Red}}{AC_{IR}/DC_{IR}}. \tag{4}$$

where AC_{Red} and AC_{IR} – alternating current components of red and infrared LEDs; DC_{Red} and DC_{IR} – direct current components of red and infrared LEDs.

Based on the calculated ratio, blood saturation is determined in percent according to the calibration characteristic of the sensor, the typical value of which is shown in figure 2. In order to use this curve for calculations, a linear approximation of the sensor characteristic is necessary. For example, the change in the characteristic shown in figure 2 when the ratio (4) changes from 0,4 to 1 can be described by the equation:

$$SpO2 \ = \ -32 \cdot (R - 0.4) + 100 \tag{5}$$

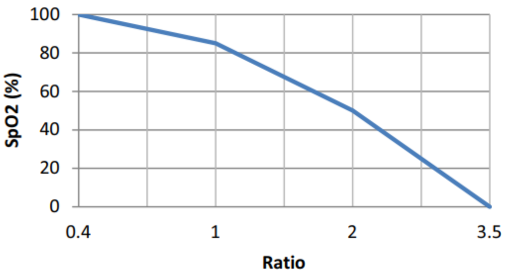


Figure 2: Sample calibration curve.

The calculation according to the given equation for $R = 1$ showed that the value of SpO2 = 80.8%. According to [15], it is stated that if the ratio $R = 1$, then blood saturation with oxygen is approximately 81%. Therefore, approximating a particular area makes it possible to carry out calculations with an acceptable accuracy for practical use.

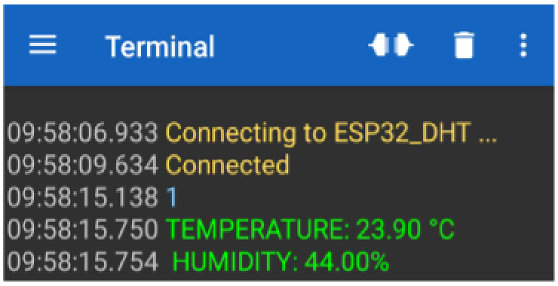
3. Results

To analyze possible options for wireless data transmission, the authors of this article implemented examples of IoT projects. They 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. Both have a built-in Wi-Fi module, and the ESP32 microcontroller supports the Bluetooth standard.

The results of the home weather station project using the ESP32 microcontroller and the DHT11 sensor are shown in figure 3. Data transmission of temperature and humidity measurements was carried out via the Bluetooth interface with the 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 a 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 measurement data were analyzed both on the transmitting and receiving sides. Figure 4 shows that 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.



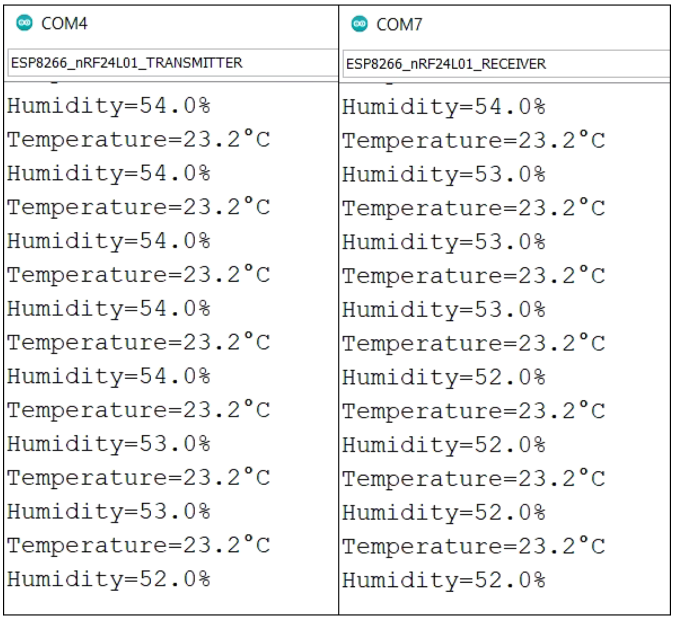
```
09:58:06.933 Connecting to ESP32_DHT ...
09:58:09.634 Connected
09:58:15.138 1
09:58:15.750 TEMPERATURE: 23.90 °C
09:58:15.754  HUMIDITY: 44.00%
```

Figure 3: Transmission of measurements via the Bluetooth interface.

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. This webpage can be accessed using any device, such as a laptop. The temperature and humidity measurement results can be displayed on a webpage using an IP address or DNS. This is shown in figure 5. Connection to the local Wi-Fi access point was conducted at a distance of at least 100 m. Using nRF24L01 transceivers increases the 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, eliminating delays in smart devices’ response to events. This is very important for motion sensors that should turn on the light after detecting a person.

ESP-NOW technology, developed by Espressif Systems, can also be used for two-way for-



```
Humidity=54.0%
Temperature=23.2°C
Humidity=54.0%
Temperature=23.2°C
Humidity=54.0%
Temperature=23.2°C
Humidity=54.0%
Temperature=23.2°C
Humidity=54.0%
Temperature=23.2°C
Humidity=53.0%
Temperature=23.2°C
Humidity=53.0%
Temperature=23.2°C
Humidity=52.0%
```

```
Humidity=54.0%
Temperature=23.2°C
Humidity=53.0%
Temperature=23.2°C
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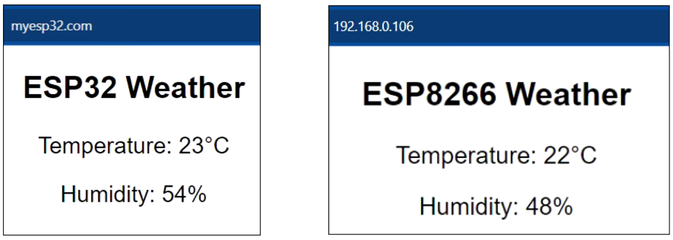
Figure 4: Transfer of temperature and humidity measurements between two transceivers nRF24L01.



ESP32 Weather

Temperature: 23°C

Humidity: 54%

ESP8266 Weather

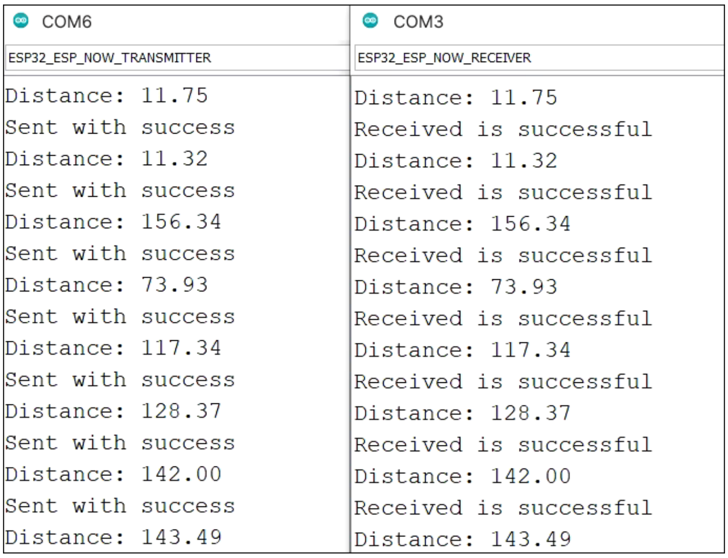
Temperature: 22°C

Humidity: 48%

Figure 5: Display of temperature and humidity measurements on a webpage.

warding 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 where 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. Suppose you must 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 in that case. 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 [3].

The results of distance measurement transmission between ESP32 controllers using ESP-NOW technology are shown in figure 6. The distance was measured by an ultrasonic sensor HC-SR04. The distance in centimetres 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 data transmission range is up to 100 m.



COM6

ESP32_ESP_NOW_TRANSMITTER

```
Distance: 11.75
Sent with success
Distance: 11.32
Sent with success
Distance: 156.34
Sent with success
Distance: 73.93
Sent with success
Distance: 117.34
Sent with success
Distance: 128.37
Sent with success
Distance: 142.00
Sent with success
Distance: 143.49
```

COM3

ESP32_ESP_NOW_RECEIVER

```
Distance: 11.75
Received is successful
Distance: 11.32
Received is successful
Distance: 156.34
Received is successful
Distance: 73.93
Received is successful
Distance: 117.34
Received is successful
Distance: 128.37
Received is successful
Distance: 142.00
Received is successful
Distance: 143.49
```

Figure 6: 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 article's authors created a gateway connecting to the Wi-Fi access point based on the ESP8266 microcontroller. Indoor air quality control sensor measurement data 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 analogue 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. A library supporting the SDA interface was used to read digital data from the DHT11 sensor. 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 SPI interface sent the gas concentration value to the nRF24L01 transceiver. 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 to transmit gas concentration measurements to ThingSpeak by connecting to a Wi-Fi access point. The change in measurements of air quality control sensors at a specific time interval, which was output to the ThingSpeak cloud service, is shown in figure 7.

It should be noted that the MQ-2 sensor does not determine the type of gas. It only reacts to increased concentrations of liquefied gas and other carbohydrates in the air. A gas lighter refill aerosol can was used to simulate an increase in LPG content in the air. Figure 7 shows that the sensor responds very well to an increase in the concentration of this gas. Blowing on

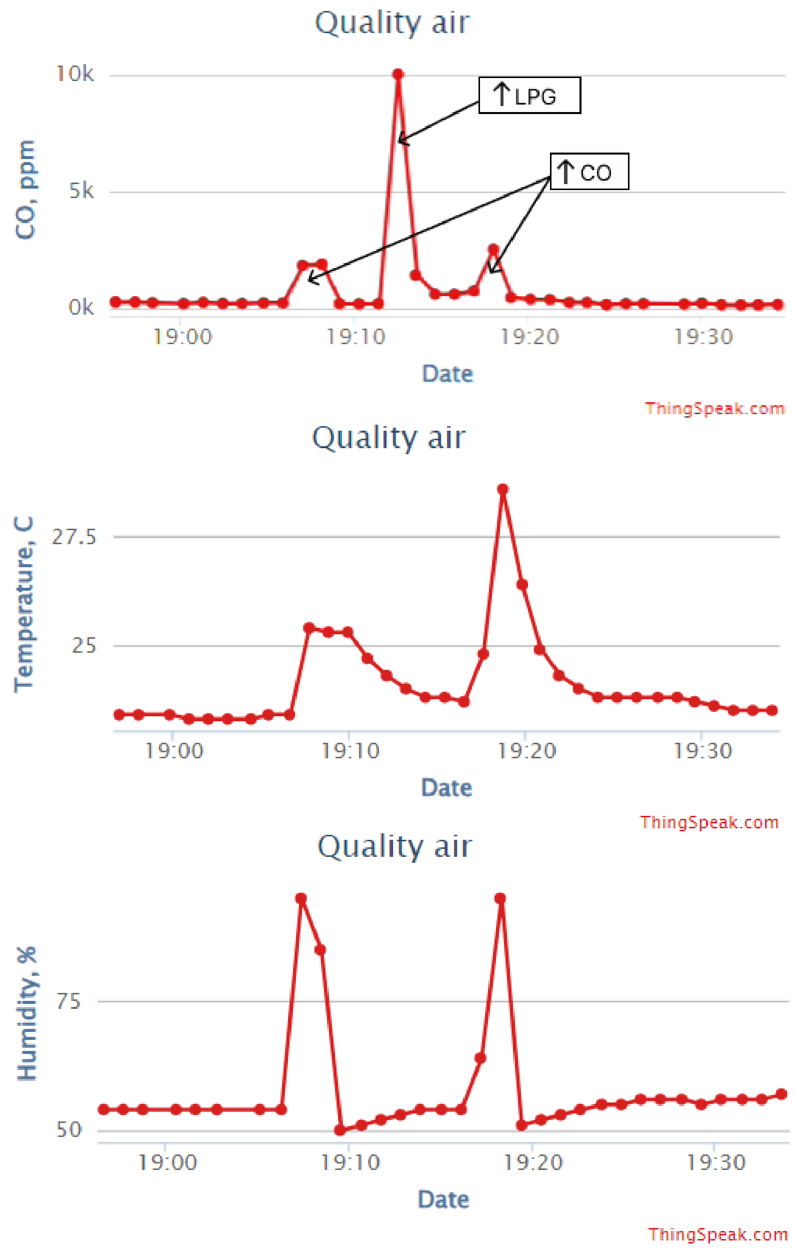


Figure 7: Display of measurements of air quality control sensors in the cloud service ThingSpeak.

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 ThingSpeak 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 [27]. An attempt to reduce the delay time or 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 8.

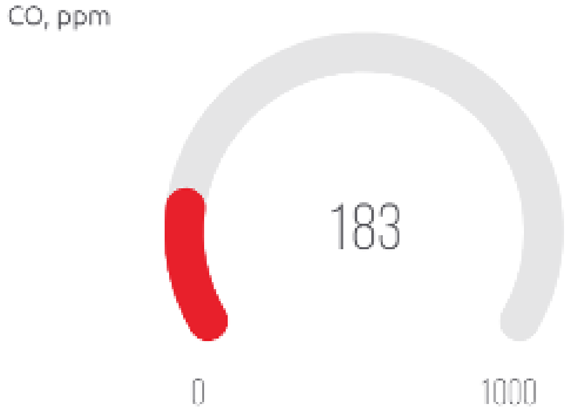


Figure 8: Display of measurements of the MQ-2 sensor in the “Blynk” cloud service.

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 data transmission range over the LoRa radio link is determined by the selected uplink (UL) and downlink (DL) parameters. These parameters in Europe are shown in table 2.

Table 2
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 3[25].

Table 3
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, provided by a LoRa radio line operating at 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 $R_b = SF \cdot BW/2^{SF}$. Using 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 4.

Table 4
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 seen from the table 4, increasing the value of SF leads to an increase in the communication range with a simultaneous decrease in the information rate of data transmission.

A practical test of the range of the radio line was carried out for the RFM95W module with FSK modulation, operating at a frequency of 868 MHz in the 125 kHz band. Moreover, the same test was conducted for the RA-01 module with LoRa modulation with a signal spectrum width of 500 kHz at a frequency of 433 MHz. Both modules have a transmitter power of 20 dBm and use non-directional antennas. The communication range of the RFM95W module in city conditions, with the location of the transmitting and receiving antennas at a height of 2m, was 100m. The communication range for the RA-01 module with Lora signal modulation (CR=4/5 and SF=10) was 1,5 km. To ensure direct visibility within the city, the transmitting antenna was located at a height of 15 m, and the receiving antenna at 2 m. The RSSI indicator, calculated in the SX1278 transceiver, was used to control the power level of the signal received by the receiver. When conducting tests in rural areas using transmitting and receiving antennas located at a height of 2m, packet loss was noted already at a distance of 600m, with an RSSI value of less than -95 dBm.

To check the correctness of blood saturation measurements according to expression (5), the paper's authors developed a portable oximeter with an MAX30102 sensor. Through the I2C interface, the sensor was connected to an ESP32 board with a built-in OLED display. Due to the lack of a hardware I2C interface, the MAX30102 sensor was connected to the ESP32 via a programmable I2C interface.

The layout of the developed device is shown in figure 9. As can be seen from this figure, the initial zero blood saturation value is displayed on the screen. Figure 10 shows the result of blood saturation measurements when a finger was placed on the sensor surface. In this case, it was 99%.

For comparison, figure 10 also shows the results of measuring blood saturation using an industrial sample C101A2 pulse oximeter. It is important to emphasize that the results of

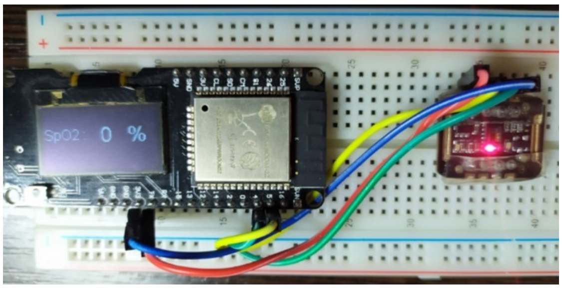


Figure 9: Layout of the developed device.

measuring blood saturation using an industrial sample C101A2 pulse oximeter also amounted to 99%, which coincided with the values of blood saturation measurements using the oximeter model developed by the authors.

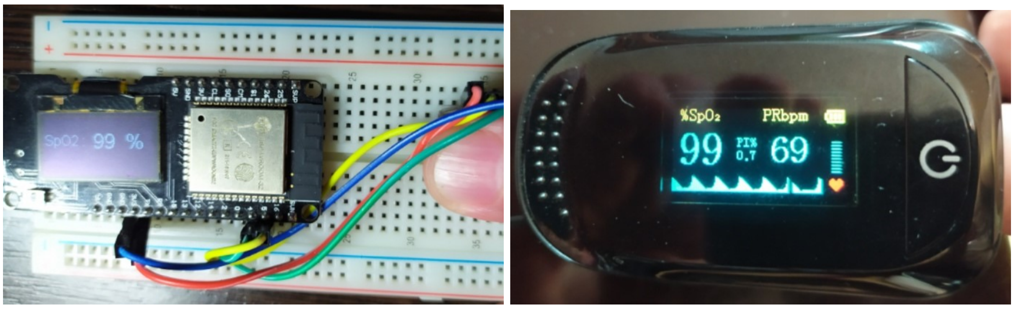


Figure 10: The result of blood saturation measurements with the developed device and the C101A2 pulse oximeter.

Moreover, an oximeter based on IoT, which can transmit the received readings wirelessly remotely to the mobile application “Blynk”, was developed. It is suggested that an ESP8266 board with an integrated Wi-Fi module and an I2C hardware interface be used. Figure **??**hows the blood saturation measurement result by the MAX30102 sensor in the Blynk mobile application are shown in figure 11.

A feature of this display mode is the gradual increase of the saturation indicator from zero to the current value and the possible change of this value during the measurement interval.

Building an IoT oximeter with feedback control using the Telegram messenger with an intuitive interface is also proposed. The ESP32 board has a built-in LED that can be turned on at the command of a pre-created “Telegram” chatbot when measurements are needed. It is also possible to give a sound signal by connecting an active or passive buzzer to the controller. The layout of the developed device is shown in figure 12. To carry out measurements, a previously created chatbot distinguishes only two commands: “/start” and “/readings”. With the “/start” command, a welcome message with instructions on how to use the chatbot is sent to the user.

The operation of the IoT oximeter begins with a connection to a Wi-Fi access point. To start testing, you must communicate with the chatbot and send the “/readings” command. With this command, the blue LED turns on, and the measurement begins. After the measurements, the

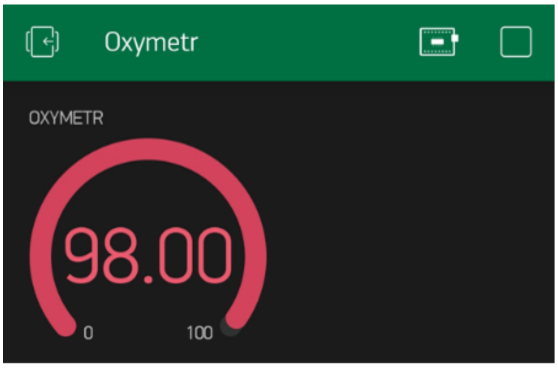
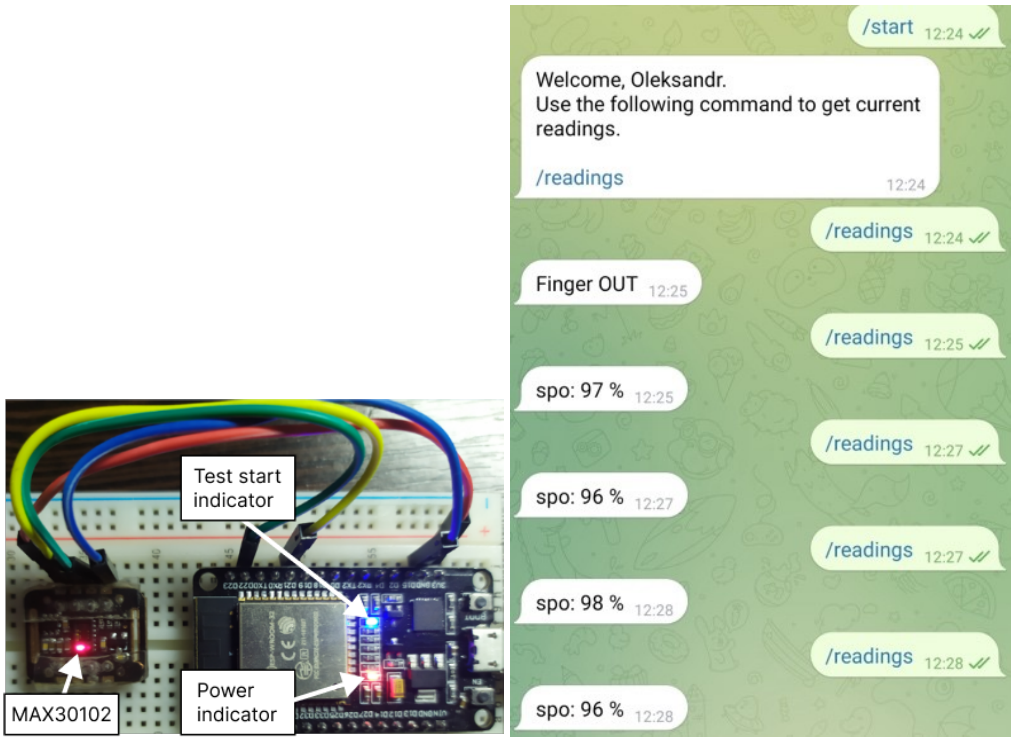


Figure 11: Display of saturation measurements in the “Blynk” mobile application.

obtained saturation value in percent will be sent to the Telegram messenger, and the LED will automatically turn off.



/start 12:24

Welcome, Oleksandr.
Use the following command to get current readings.

/readings 12:24

/readings 12:24

Finger OUT 12:25

/readings 12:25

spo: 97 % 12:25

/readings 12:27

spo: 96 % 12:27

/readings 12:27

spo: 98 % 12:28

/readings 12:28

spo: 96 % 12:28

Figure 12: IoT oximeter on ESP32.

If the finger is not placed on the sensor, the message “Finger OUT” is sent. The doctor can request a repeat measurement by sending the command “/readings” if necessary. As seen from figure 12, the measured value of saturation may differ insignificantly in different test sessions.

4. Discussion

4.1. Related works

The findings of this study contribute to the growing body of knowledge on wireless data transmission and computing paradigms in IoT applications. Our work aligns with the research of Xue et al. [30], who emphasized the importance of edge computing in reducing latency and increasing the responsiveness of IoT systems. However, our study extends their work by providing practical examples and performance metrics for various wireless technologies, such as ESP-NOW, nRF24L01, and Bluetooth.

The use of the Okumura-Hata model for estimating signal loss in LoRa radio lines, as demonstrated in our work, is consistent with the approach adopted by Ferreira et al. [5], Lima et al. [11], Pinto-Erazo et al. [17]. Nevertheless, our study goes beyond theoretical calculations by validating the range of LoRa radio lines through practical implementations using RFM95W and RA-01 modems. This experimental validation strengthens the reliability of our findings and offers insights for real-world deployments.

The edge and cloud computing integration in our IoT projects aligns with the architectural frameworks described by Kumar and Agrawal [10]. The successful implementation of remote monitoring applications, such as the IoT oximeter with feedback control, demonstrates the feasibility and potential of leveraging these computing paradigms in healthcare scenarios.

While our study focuses on specific wireless technologies and computing approaches, it is essential to acknowledge the diverse range of solutions available in the IoT landscape. The works of Bayılmış et al. [1] and Ray [21] provide comprehensive surveys of IoT communication protocols and architectures, respectively. Our findings contribute to this broader context by offering detailed insights into selected technologies' performance and practical considerations.

4.2. Anomalies and unexpected results

During our experiments, we encountered some anomalies and unexpected results that warrant further discussion.

One unexpected result was the variation in the range of LoRa radio lines using RFM95W and RA-01 modems. In our experiments, the RFM95W module with FSK modulation achieved a communication range of 100 meters in urban environments. In contrast, the RA-01 module with LoRa modulation reached a range of 1.5 kilometres under similar conditions. This significant difference in range highlights the impact of modulation techniques and hardware choices on the performance of LoRa networks. Further investigation into the factors contributing to this variation, such as antenna design, environmental conditions, and software configurations, could provide valuable insights for optimizing LoRa deployments.

During our air quality monitoring system experiments, we noticed that the MQ-2 gas sensor exhibited sensitivity to factors other than the target gases. For example, changes in humidity and temperature led to variations in the sensor's output, even in the absence of target gases. This cross-sensitivity highlights the need for careful calibration and compensation techniques to mitigate the impact of environmental factors on gas sensor performance. Incorporating additional sensors for temperature and humidity monitoring and advanced signal processing algorithms could help improve the accuracy and reliability of air quality monitoring systems.

4.3. Limitations and assumptions

While our study provides valuable insights into the practical aspects of wireless data transmission and the integration of edge and cloud computing in IoT applications, it is essential to acknowledge the limitations and assumptions that may have influenced our findings.

One of the main limitations of our study is the focus on a specific set of wireless technologies, such as ESP-NOW, nRF24L01, Bluetooth, and LoRaWAN. While these technologies are widely used in IoT applications, our experiments did not cover some other protocols and standards. Future research could explore a broader range of wireless technologies to analyse their performance and suitability for different IoT scenarios comprehensively.

Another limitation is the scale of our experiments. Due to resource constraints, our IoT projects were implemented in controlled environments with a limited number of devices. In real-world deployments, IoT systems may involve many devices, which could impact the performance and reliability of the wireless networks. Future studies could investigate the proposed solutions' scalability and performance in large-scale IoT deployments.

We made certain assumptions regarding the operating conditions and device configurations during our experiments. For example, we assumed that the devices operated in an interference-free environment and that the antennas were optimally positioned. In practical scenarios, factors such as interference from other devices, obstacles, and suboptimal antenna placement can affect the performance of wireless communication. Future research could investigate the impact of these factors on the reliability and efficiency of IoT systems.

5. Conclusions

The use of edge computing in IoT technology reduces system response delays to sensor output signals and increases the network's throughput. This type of distributed computing is always carried out near the edge devices. Therefore, edge computing takes place to create sensor networks in 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 creating 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 absolute sensitivity values of the receiver. The Okamura-Hata radio wave propagation model was proposed to estimate the LoRa radio line's total loss. The obtained values of the radio line range make it possible to more accurately determine the WSN coverage area using the LoRaWAN communication protocol. The range of the LoRa radio line with various modulation types was practically determined by implementing IoT projects using RFM95W and RA-01 modems. The essence of edge computing with combined digital and analogue sensors is shown. A device for remote monitoring of oxygen saturation in patients' blood at home at the request of a doctor and display of test results using the Telegram messenger was developed. A practical check of the correctness of blood saturation measurements was carried out. 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.

Author contributions

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

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

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