DESIGN AND IMPLEMENTATION OF A MULTI-TECHNOLOGY WIRELESS SENSOR NETWORK FOR CONDITION MONITORING

ROBERT RAKAY[1], PATRIK SARGA[1], ERIK PRADA[1]

[1]Technical University of Kosice, Faculty of Mechanical Engineering, Kosice, Slovakia

DOI: 10.17973/MMSJ.2025_12_2025111

patrik.sarga@tuke.sk

The article discusses the design and testing of a wireless sensor network utilizing multiple communication technologies to achieve low power consumption and extended transfer distances. The sensorial nodes gather data and send it to a central module, which provides a monitoring window. The sensor nodes are designed for educational purposes, enabling students to conduct training experiments focused on creating wireless monitoring systems for industrial and general applications.

KEYWORDS

sensor, wireless, IoT, mechatronics, LoRa, condition monitoring

1 INTRODUCTION

The ongoing digital transformation in industrial automation is creating new approaches to monitor production processes, where the collection and processing of data are becoming key factors. This shift, known as Industry 4.0, is closely tied to the benefits of the Industrial Internet of Things (IIoT), where sensors, controllers, and wireless communication interfaces form a unified system [Basir 2019, Lampropoutos 2019, Alabadi 2022, Wojcicki 2022, Demcak 2024]. Based on these advantages, new applications and options are created to monitor production systems, analyse data, and effectively control processes.

The right choice of communication protocols is the key to success. Industrial applications often require a combination of technologies for both interior and exterior environments – from warehouse production lines to challenging outdoor areas. Wireless nodes, which integrate sensors and control devices, provide a flexible solution that allows the connection of multiple parts of the production line to the company network, typically using Wi-Fi or other specialized, low-power-consuming protocols such as LoRaWAN [Vitturi 2019, Liu 2019].

The primary objective of the article is to propose and test a sensor network that integrates two separate wireless networks and sensor nodes. The first sensor node is suited for indoor use, such as production warehouses; the second node is designed for outdoor operation.

The upcoming testing and implementation are scheduled for the model industrial production line situated at the automation laboratory within the Department of Industrial Automation and Mechatronics [Romancik 2024].

The measured data is collected and further processed at the company network level, where it can be further processed and visualized. For users, a web server will be created on the central unit, providing access to measured data with a basic view and a historical trend of ongoing values. In the case of the external unit, a maximal communication distance is tested.

The primary outcome of this work is the design and implementation of a prototype solution for a monitoring sensor network based on IoT technology, which incorporates low-cost hardware, flexible communication protocols, and software support for data visualization. The system provides a functional base that can be developed and adapted for real-world applications and specific production parameters.

2 INTERNET OF THINGS

Information and communication technologies (ICT) in the IoT sphere represent a revolutionary way of transporting data (information) between people, people and devices, and between different devices. Smart devices can connect, send data (information), and make decisions without human intervention. This modern technology is also referred to as “connectivity for anything”, which translates to “connection with anything”. We can connect anywhere, anytime, and with anything.

The IoT environment consists of a massive number of “smart devices”, but with several limitations, such as limited memory for storing processed data, a short lifespan, and the limited wireless range they can create. Therefore, we need to use the implementation of IoT protocols, which can help effectively eliminate the shortcomings we have mentioned.

There are many communication protocols available, suitable for long distances of kilometers or for fast events that communicate over a few meters. We cannot determine one main criterion that would apply to the selection of the best protocol. Because each application has different requirements in terms of specific software or hardware. We can only determine this by a thorough analysis of the problem. Our analysis can consist of several areas that will help us select the best protocol, and these are [Brachmann 2016, Hedi 2017, Islam 2024, Sidna 2020, Neyestanak 2021]:

- Range
- Bandwidth
- Coverage
- Power consumption
- Reliability
- Delay / Response
- Price-performance ratio

These main criteria, which can be changed according to the customer or project specifications, will save us both financial and project time to complete the application.

The most common communication protocols are described and characterized in the comparison Table 1. The list of analysed protocols includes protocols suitable for short and long ranges, as well as for high and low transfer rates. While the list includes 10 protocols, there are many other, not highlighted ones that are sometimes limited to special hardware or license policies as well.

These IoT protocols offer a range of options and power requirements to suit various needs. SigFox and LoRa excel in long-range, low-power communications with small data payloads. They are ideal for environmental and smart city applications. Cellular and Wi-Fi applications require more energy. Lastly, 6LoWPAN, ZigBee, BLE, RFID, NFC, and Z-Wave protocols are typically used for short-range, low-power network systems, often implemented in industrial and home environments [Almuhaya 2022, Froiz-Miguez 2020, Bhatia 2023, Sarga 2023].

Table 1. Comparison of selected IoT communication protocols

Technology	Range	Data Transfer Rate	Power Consumption	Network Topology	Main Applications	Significant for
SigFox	Up to 50 km	10 - 1000 bits/s	Very low	Mainly star, simple	Agriculture, smart meters, security	Ultra Narrow Band, very low battery usage
Cellular 3G/4G/5G	Long distances	High	Higher	Wide area (Internet)	Mobile devices, commercial applications	Suitable for high data volumes, energy-intensive
6LoWPAN	Short to medium distances	Medium	Low	Star, mesh	IP-based IoT networks	Supports IPv6, IEEE 802.15.4
ZigBee	Up to 100 m	Lower than 6LoWPAN	Low	Star, mesh, tree	Home automation, industrial	Faster response than 6LoWPAN
BLE	Up to 50 m	Low	Very low	Star	Short range, wearables, sensors	Short setup time, low power consumption
RFID	Passive: cm, Active: up to 100 m	Low	Active: higher, Passive: none	Point-to-point	Identification, asset tracking	Not usable for sensor measurements
NFC	Up to 10 cm	Low	Low	Point-to-point (close contact)	Payments, mobile devices, control	Bidirectional communication, rewritable data
Z-Wave	Up to 30 m	Up to 100 kbps	Low	Mesh	Home automation, healthcare	Master-slave device roles
Wi-Fi	Up to 100 m (environment-dependent)	High	Higher	Star	Local networks, Internet	High power usage, multiple standards
LoRa/LoRaWan	Several km (commonly 1-15 km)	Low to medium	Very low	Star	Wide-area IoT, smart cities, agriculture	Uses low frequencies, adaptive data rate

3 MODEL OF THE INDUSTRIAL PRODUCTION SYSTEM

The conceptual purpose of the sensor network design is to gather and monitor production parameters of the FMS-500 production line model. This system was designed for educational purposes, specifically for students in higher education and universities. The main fields that are available focus on mechatronics, pneumatics, industrial sensors, industrial networking, and robotics [Vagas 2024].

In its current configuration, the production line comprises four stations and a single transport system. (Fig.1)

1- Testing and distribution station
2- Processing station
3- Assembly station
4- Sorting station
5- Transport system

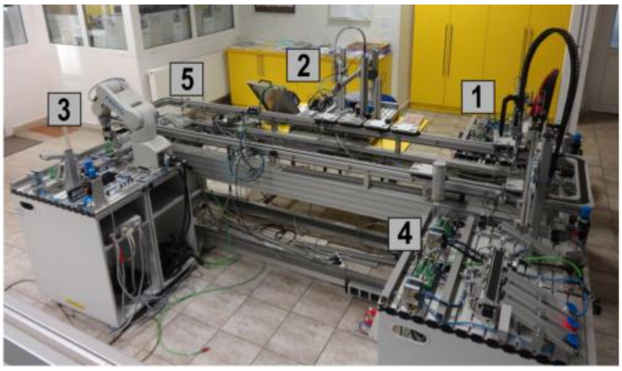

Figure 1. Model production system FMS-500

3.1 *Condition monitoring*

In response to the pressure of competition, producers must increase the overall effectiveness of their production systems while simultaneously reducing downtime. This requires technologies that help to simplify maintenance and maximize production reliability. Condition monitoring provides access to the current state of devices and systems for maintenance with maximum optimisation effort. Typical parameters monitored in industrial and other environments include temperature, pressure, humidity, vibrations, fluid flow, electric current, and chemical composition. These measurements are obtained using specialized sensors and processed with software for diagnostic purposes and maintenance planning, ensuring the safety, performance, and optimal operation of equipment and processes [Kelemen 2014, Zidek 2018, Krenicky 2021, Vagas 2021].

There are multiple approaches available from different vendors for gathering such data from production systems. Some of these create predictive estimation of future states, malfunctions, or errors. Multiple vendors focus on monitoring parameters as vibrations and temperature, which significantly improve the insight into the state of rotating machines. Other existing solutions also include finding relations between already measured characteristics.

4 SYSTEM DESCRIPTION - SENSOR NODES

The proposed solution focuses on the design of the monitoring nodes, each node will be characterized by its unique functionality and access to processed data. Instead of a direct comparison of protocols through which processed data passes, we are considering emphasizing their individual capabilities and benefits. The aim is to identify the optimal placement of these nodes within the data collection process. When selecting protocols, we followed the available options for utilizing existing devices at the faculty.

The experimental system consisted of environmental sensors, including temperature and humidity, as well as a current sensor. (Fig.2) These sensors provide us with data for experimentation and analysis. Suppose the system is integrated into the production line model. In that case, other sensors have been applied, such as vibration sensors, noise sensors, and gas analysis sensors, depending on the station where the node is placed.

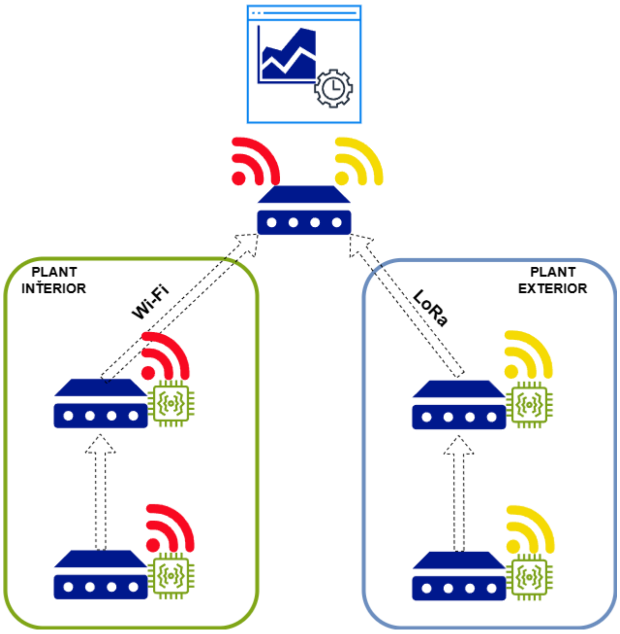

Figure 2. Model production system FMS-500

4.1 The central unit

The proposed superior communication node is proposed for the centralized collection of data from all the other devices (Fig. 3). This node is implemented using the ESP32 microcontroller and enables the interconnection of Wi-Fi and LoRaWAN networks. The LoRaWAN connection is built on SX1278 modules with an external antenna.

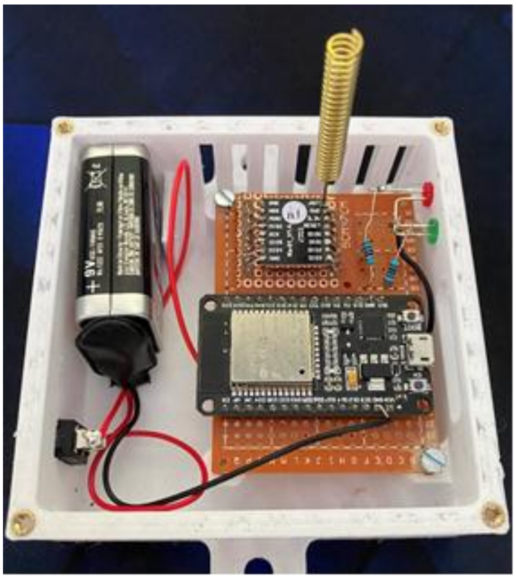

Figure 3. Central unit

The central unit solves 3 tasks:

- Receiving data via Wi-Fi,
- Receiving data via LoRaWAN,
- Processing and visualizing data.

The working principle of the central unit is described using pseudocode:

```
START

Initialize LoRa module
Initialize Wi-Fi module
IF Initialize successful THEN
    Turn on OK LED
ELSE
    Turn on NOK LED
END IF
Turn on data receiving
WHILE TRUE DO
    IF data receiving THEN
        Save data for Webserver
        Send data to Webserver
        STOP
    ELSE
        Continue
    END IF
END WHILE
END
```

4.2 LoRa Network unit

As previously described, the exterior unit will communicate using the LoRa Network. The main processing device for this unit will be Arduino UNO Rev 3. (Fig.4) The sensors connected to the microprocessor are current sensors, temperature and humidity sensors. To indicate diagnostic status, OK LED and Error LED are added. The circuit diagram of the LoRa unit is shown below.

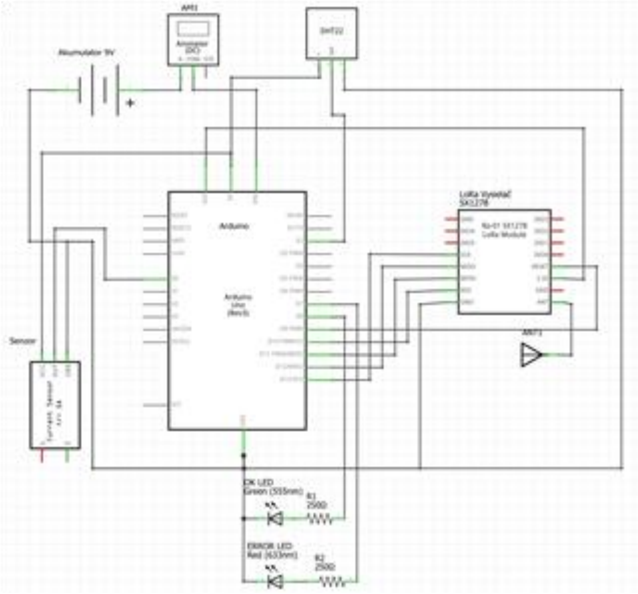

Figure 4. Circuit diagram of LoRa unit

4.3 Webserver

The collected data is processed in JSON format. To create a local webserver, HTML code with JavaScript and CSS was used. For testing purposes, no restrictions were made regarding the security of the webserver. The webpage is available via the IP address of the central unit via any Wi-Fi capable device on the same network. (Fig.5)

The monitoring window is divided into two main parts. The first numerical part displays the most recently received values. In contrast, the second part graphically visualizes the measured temperature, humidity, currents from LoRa and Wi-Fi nodes, along with the strength of the wireless signal.

Figure 5. Webserver on central unit

5 TESTING FOR EXTERIOR

Tests were performed exclusively in the exterior, as the interior area already has an existing Wi-Fi network for wireless integrations. As a test value, the signal strength (RSSI) of the LoRa transmitter was used, since it is a long-range device intended for outdoor use. The experiment was conducted in an urban area with a few tall trees and medium-sized bushes as the surrounding environment. There was also moderate traffic on the street during the test, which could also affect the signal strength. The received values were measured 5 times for each distance, and the average value is collected in the following result Table 2.

Tab 2. Measurement results

Distance [m]	RSSI [dBm]	Distance [m]	RSSI [dBm]
5	-52	100	-86
10	-50	120	-81
15	-47	130	-72
20	-55	140	-84
30	-64	150	-80
40	-61	160	-88
50	-66	170	-84
60	-70	180	-88
70	-71	190	-88
80	-82	200	-89
90	-79		

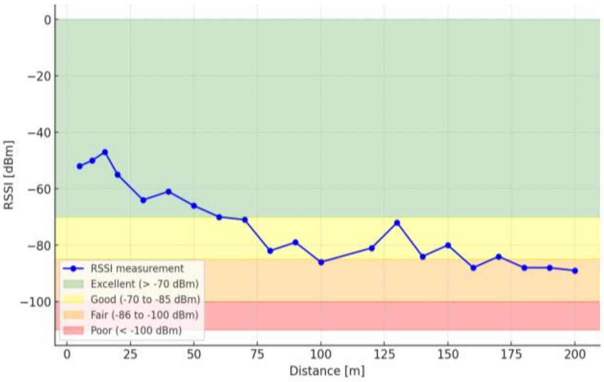

Figure 6. The RSSI measurement results

The longest acceptable connection between the transmitter and receiver was 200 meters. The quality of the measured RSSI is graphically visualized in the following Fig. 6 with highlighted intervals of the signal quality.

Further testing successfully resulted in a maximal communication distance of 500 meters, but with low RSSI quality.

6 CONCLUSIONS

Monitoring of the overall status of production systems is critical for saving the cost of maintenance. Modern communication protocols, combined with microprocessors, can provide a solid foundation for both interior and exterior wireless sensor networks. Measurement of actual parameters, such as temperature, humidity, and vibration, on current consumption provides a more accurate view of the actual situation at the integration site. Different IoT communication protocols support various use cases.

In this paper, a wireless sensor network system is proposed for monitoring industrial production systems. First, the relevant technical parameters are measured at the sensor nodes. This information will be communicated to a central unit. Here, data from the other wireless networks is also being collected. Lastly, a visualization of the gathered data is created using an internal webserver. Here, numerical and graphical elements highlight the actual and historical values.

The wireless communication of the LoRa modules was tested for signal quality in an urban environment. With the current hardware configuration, the maximum stable connection was achieved at a distance of 200 meters. The study demonstrates that low-cost microcontrollers, when combined with suitable sensors, can effectively provide valuable information about industrial systems. The proposed wireless sensor network, with minor modifications, can be adapted to collect environmental and technical data of production systems.

ACKNOWLEDGMENTS

The authors would like to thank the Slovak Grant Agency project VEGA 1/0169/22 and grant project KEGA 016TUKE-4/2025 supported by the Ministry of Education of the Slovak Republic.

REFERENCES

[Alabadi 2022] Alabadi, M., Habbal, A., Wei, X. Industrial Internet of Things: Requirements, Architecture, Challenges, and Future Research Directions. IEEE Access, 2022, Vol. 10, pp. 66374-66400. https://doi.org/10.1109/access.2022.3185049.

[Almuhaya 2022] Almuhaya, M.A.M., Jabbar, W.A., Sulaiman, N., Abdulmalek, S. A Survey on LoRaWAN Technology: Recent Trends, Opportunities, Simulation Tools and Future Directions. Electronics, 2022, Vol. 11, 164. https://doi.org/10.3390/electronics11010164.

[Basir 2019] Basir, R., et al. Fog Computing Enabling Industrial Internet of Things: State-of-the-Art and Research Challenges. Sensors, 2019, Vol. 19, No. 21, 4807. https://doi.org/10.3390/s19214807.

[Brachmann 2016] Brachmann, M., Landsiedel, O., Santini, S. Concurrent Transmissions for Communication Protocols in the Internet of Things. In: 2016 IEEE 41st Conf. on Local Computer Networks (LCN); Dubai, UAE, 2016, pp. 406-414. https://doi.org/10.1109/lcn.2016.69.

[Bhatia 2023] Bhatia, S., Jaffery, Z. A., Mehfuz, S. A Comparative Study of Wireless Communication Protocols for use in Smart Farming Framework Development. In: 2023 3rd Int. Conf. on Intelligent Communication and Computational Techniques (ICCT); Jaipur, India, 2023, pp. 1-7. https://doi.org/10.1109/icct56969.2023.10075696.

[Demcak 2024] Demcak, J., Zidek, K., Krenicky, T. Digital Twin for Monitoring the Experimental Assembly Process Using RFID Technology. Processes, 2024, Vol. 12, No. 7. DOI: 10.3390/pr12071512.

[Hedi 2017] Hedi, I., Speh, I., Sarabok, A. IoT network protocols comparison for the purpose of IoT constrained networks. In: 2017 40th International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO); Opatija, Croatia, 2017, pp. 501-505. https://doi.org/10.23919/mipro.2017.7973477.

[Islam 2024] Islam, M., Jamil, H., Das, R., et al. Future Industrial Applications: Exploring LPWAN-Driven IoT Protocols. Sensors, 2024, Vol. 24, No. 8, 2509. https://doi.org/10.3390/s24082509.

[Froiz-Miguez 2020] Froiz-Miguez, I., et al. Design Implementation, and Empirical Validation of an IoT Smart Irrigation System for Fog Computing Applications Based on LoRa and LoRaWAN Sensor Nodes. Sensors, 2020, Vol. 20, No. 23, 6865. DOI: 10.3390/s20236865.

[Kelemen 2012] Kelemen, M., et al. Design and Development of Lift Didactic Model within Subjects of Mechatronics. Procedia Eng., 2012, Vol. 48, pp. 280-286. DOI: 10.1016/J.PROENG.2012.09.515.

[Kelemen 2014] Kelemen, M., et al. Rapid Control Prototyping of Embedded Systems Based on Microcontroller. Procedia Engineering, 2014, Vol. 96, Issue 11, pp. 215-220. ISSN 1877-7058.

[Krenicky 2021] Krenicky, T., Nahorny V. Trend forecast for short-term of shock-vibration prediction. In: MM Science Journal, 2021, Vol. October, pp. 4786-4790. DOI: 10.17973/MMSJ.2021_10_2021040.

[Lampropoulos 2019] Lampropoulos, G., Siakas, K., Anastasiadis, T. Internet of Things in the Context of Industry 4.0: An Overview. Int. J. of Entrepreneurial Knowledge, 2019, Vol. 7, No. 1. https://doi.org/10.37335/ijek.v7i1.84.

[Liu 2019] Liu, X., Wei, X., Liu, Y., et al. Turning the Signal Interference Into Benefits: Towards Indoor Self-Powered Visible Light Communication for IoT Devices in Industrial Radio-Hostile Environments. IEEE Access, 2019, Vol. 7, pp. 24978-24989. https://doi.org/10.1109/access.2019.2900696.

[Neyestanak 2021] Neyestanak, M.S., Azizi, E., Salarpour, E. IoT Performance Improving for Indoor and Outdoor Environments. In: 2021 5th International Conference on Internet of Things and Applications (IoT), Isfahan, Iran, 2021, pp. 1-6. DOI: 10.1109/IoT52625.2021.9469604.

[Romancik 2024] Romancik, J., et al. Design, Implementation, And Testing of a 3D printed Gripper Actuated by Nitinol Springs. MM Science J., 2024, Vol. June, pp. 7352-7356. DOI: 10.17973/MMSJ.2024_06_2024009.

[Sarga 2023] Sarga, P., et al. Testing of transfer RF-based system. MM Science Journal, 2023, Vol. October, pp. 6644-6649. DOI: 10.17973/MMSJ.2023_10_2023011.

[Sidna 2020] Sidna, J., Amine, B., El Alami, H., Abdallah, N. Analysis and evaluation of communication Protocols for IoT Applications. In: Proc. of the 13th Int. Conf. on Intelligent Systems: Theories and Applications (SITA'20). Association for Computing Machinery, New York, USA; Article 42. https://doi.org/10.1145/3419604.3419754.

[Vagas 2022] Vagas, M., et al. Testing of Ethernet-based communication between control PLC and collaborative mechatronic system. In: 20th Int. Conf. on Mechatronics (ME); Pilsen, Czech Republic, 2022. DOI: 10.1109/ME54704.2022.9983428.

[Vagas 2021] Vagas, M., et al. Testing of Selected Accuracy Parameters for the Single Axis Positioner at the Automated Workplace. Measurement Science Review, 2021, Vol. 21, pp. 47-54. DOI: 10.2478/msr-2021-0007.

[Vagas 2024] Vagas, M., et al. Implementation of IO-the Handling and Sorting Sub-Station of the Festo FMS 500 Automated Line. MM Science Journal, 2024, Vol. June, pp. 7348-7351. DOI: 10.17973/MMSJ.2024_06_2024008.

[Zidek 2018] Zidek, K., et al. Auxiliary Device for Accurate Measurement by the Smart vision System. MM Science Journal, 2018, No. March, pp. 2136-2139. DOI: 10.17973/MMSJ.2018_03_201722.

CONTACTS:

Patrik Sarga, Assoc. Prof., Ing., PhD.
Technical University of Kosice, Faculty of Mechanical Engineering
Institute of Automation, Mechatronics, Robotics and Production Techniques
Letna 9, 04200 Kosice, Slovak Republic
patrik.sarga@tuke.sk