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Evaluación Comparativa de Redes IoT en Agricultura de Precisión

Comparative Evaluation of IoT Networks in Precision Agriculture

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Resumen

La agricultura de precisión se ha posicionado como una herramienta esencial en la modernización de las prácticas agrícolas, maximizando eficiencia y productividad. Sin embargo, la correcta selección de una red de comunicación es crucial para la eficaz transmisión de datos en este ámbito. Ante la diversidad de redes IoT disponibles, surge la interrogante sobre cuál es la más adecuada en términos de alcance, consumo energético y confiabilidad. Esta investigación abordó la evaluación comparativa de cinco prominentes redes IoT para discernir sus aplicabilidades. Utilizando sensores IOT-S300SMT y distintos módulos representativos, LoRaWAN emergió como la red más destacada en términos de alcance y equilibrio energético. Aunque ZigBee y Z-Wave presentaron ventajas en latencia y aplicaciones en tiempo real, LoRaWAN se consolidó como la opción más versátil. Estos hallazgos ofrecen una guía valiosa para profesionales del sector agrícola, enfatizando la importancia de una adecuada selección de redes IoT para la agricultura de precisión.

Palabras clave: Agricultura de Precisión, Redes IoT, Monitoreo Agrícola.

Abstract

Precision agriculture has established itself as an essential tool in the modernization of farming practices, maximizing efficiency and productivity. However, the correct choice of a communication network is crucial for the effective data transmission in this field. Given the variety of available IoT networks, a question arises about which one is the most suitable in terms of range, energy consumption, and reliability. This research tackled the comparative evaluation of five prominent IoT networks to discern their applicabilities. Using IOT-S300SMT sensors and various representative modules, LoRaWAN emerged as the most outstanding network in terms of range and energy balance. Although ZigBee and Z-Wave presented advantages in latency and real-time applications, LoRaWAN established itself as the most versatile option. These findings offer valuable guidance for professionals in the agricultural sector, emphasizing the importance of the right IoT network selection for precision agriculture.

Keywords: Precision Agriculture, IoT Networks, Agricultural Monitoring.

Introduction

Agriculture, one of humanity's most ancient practices, has undergone radical transformations throughout millennia, adapting and evolving with the technology available in each era (Koohafkan & Altieri, 2010). In recent decades, the technological revolution has significantly impacted the way farmers cultivate, manage, and monitor their lands (Cruz Bello, 2023). One of the most notable innovations in this realm is precision agriculture, an approach that merges advanced technologies with traditional farming practices to maximize efficiency and productivity (Cisternas, Velásquez, Caro, & Rodríguez, 2020).

At the heart of this revolution is the Internet of Things (IoT). Through sensors, devices, and advanced communication networks, detailed information about soil conditions, climate, crop health (Murrieta Ronquillo, 2023), and other critical factors can be obtained in real-time (Sott et al., 2020). This monitoring capability and the ability to respond to changing conditions might be the difference between a successful harvest and a season of losses.

However, implementing IoT solutions in agricultural settings poses unique challenges (Mejía Ortiz, 2022). Unlike urban or industrial applications, where network infrastructure is typically robust and reliable, agricultural fields can span vast areas, often in remote regions with limited connectivity access (Bernal-Jiménez & Rodríguez-Ibarra, 2019). Furthermore, environmental factors, such as topography, vegetation, and weather conditions, can significantly impact data transmission, demanding specialized network solutions (Berral, 2020).

Given the proliferation of IoT technologies and networks available, there's an urgent need to assess and compare their applicability and efficacy in an agricultural context. Which network is best suited for long-range data transmission across extensive fields? Which technology offers the optimal balance between energy consumption and reliability? These are just some of the questions this study aims to answer.

With this research, we aspire to provide a detailed and objective guide for farmers, researchers, and industry professionals by presenting a rigorous comparative evaluation of the leading IoT networks in the realm of precision agriculture. In doing so, we hope to contribute to the sustainable growth and development of 21st-century agriculture, ensuring that farmers have access to the best available technology to tackle present and future challenges (Soto, Suárez, Rodríguez, & Cainaba, 2019).

While this study focuses on precision agriculture, it is crucial to recognize the versatility and potential of IoT networks in a variety of applications beyond agriculture. From environmental monitoring to natural resource management and logistics in rural environments, IoT solutions offer significant opportunities to enhance efficiency and sustainability. In evaluating IoT networks in this study, we also consider their applicability in these diverse contexts, providing a framework that benefits multiple sectors and contributes to sustainable technological development at both regional and global levels.

The choice to focus this study on precision agriculture is not arbitrary. This field represents a critical area where the integration of IoT technologies can have a transformative impact. With the increasing demand for food and the current environmental challenges, precision agriculture offers a promising solution for enhancing agricultural productivity and sustainability. Through the use of IoT networks, more efficient resource management, cost reduction, and minimization of environmental impact can be achieved. This study aims to contribute to this growing area of importance, offering valuable insights into how IoT technologies can be best implemented and optimized in the agricultural context.

Materials and Methods

The primary objective of this study was to evaluate and compare the performance of different IoT networks in a real agricultural setting, to determine which one is most suitable for precision agriculture applications. To achieve this, a series of tests and measurements were conducted on a specific agricultural site, using various modules and sensors.

Study Site:

The selected agricultural plot is located in El Tajito, Guasave, Sinaloa, covering a total area of 8.01 hectares with geographical coordinates 25°39'18" N and 108°38'14" W. This plot was chosen due to its representation of the typical agricultural conditions of the region. Tests were conducted over a full cultivation period, capturing seasonal variations and fluctuating climatic conditions.

1 - Selection and Description of Networks and Modules:

Given the specific demands of precision agriculture and the need for robust and reliable communication systems, five IoT networks were chosen that have shown potential in agricultural settings. Each network was assessed using a representative module, considering factors such as range, penetration capability, energy consumption, and adaptability to the conditions of the plot.

- LoRaWAN:

  LoRaWAN has emerged as one of the leading IoT technologies for agriculture due to its ability to transmit over long distances with low energy consumption (Oquelis Guerrero & Landa Vega, 2020). The Semtech module is widely recognized in the literature for its performance and reliability in agricultural applications (Belupú Amaya, 2023). Figure 1 shows the Semtech SX1276 module, a long-range radio transceiver used in IoT applications and low-power wireless communication.

Figure 1. Semtech SX1276 Module.

- NB-IoT:

  NB-IoT has been identified as an optimal solution for applications requiring infrequent and low-power transmissions in rural areas (Valecce, Petruzzi, Strazzella, & Grieco, 2020). The Quectel BC95 module is a leading solution in this field, providing reliable communications in rural areas and zones with weak signal (Ye, Yang, & Zhu, 2021). Figure 2 displays the Quectel BC95 module, specifically designed for NB-IoT communication.

Figure 2. Quectel BC95 Module.

- Sigfox:

  Sigfox is an LPWAN solution that focuses on small, sporadic messages, making it ideal for sensors transmitting data infrequently (Pitu & Gaitan, 2020). The Wisol WSSFM10R2AT module allows devices to connect reliably to the Sigfox network (Langer, Leones Bazzi, & Lopez Sepulveda, 2020). Figure 3 displays the Wisol WSSFM10R2AT module, used to facilitate connection to the Sigfox network.

Figure 3. Wisol WSSFM10R2AT Module.

- ZigBee:

  ZigBee is a mesh network that allows devices to communicate with each other, retransmitting messages through intermediate nodes (Ramani, 2021). It is especially useful in environments where a high node density is required. The XBee S2C module is a proven solution that facilitates the creation of efficient ZigBee networks (Koodtalang & Sangsuwan, 2020). Figure 4 displays the XBee S2C module, widely used for ZigBee implementations.

Figure 4. XBee S2C Module.

- Z-Wave:

  Z-Wave is a technology geared towards home automation but has found applications in agriculture, especially in irrigation systems and monitoring (Babakhouya, Naji, Hnini, & Daaif, 2023). The ZM5304 module provides reliable Z-Wave communications and easily integrates with a variety of sensors and actuators. Figure 5 displays the ZM5304 module, specialized in Z-Wave communications.

Figure 5. ZM5304 Module.

2 - Experimental Design:

- Sensor Distribution: To ensure uniform coverage and appropriate representation of the field, sensors were distributed in a grid layout. Each sensor was placed 90 meters apart from its nearest neighbor, forming a mesh arrangement that spanned the entirety of the agricultural plot.
- Sensor-to-Module Connection: Each IOT-S300SMT sensor was connected to one of the representative modules from the LoRaWAN, NB-IoT, Sigfox, ZigBee, and Z-Wave networks. This setup allowed for the evaluation of the performance of each network under equal conditions.
- Network Parameter Configuration: For each network, specific transmission parameters were set up:
  a) Transmission Rate: 9600 bits per second (bps). This rate was adjusted based on the manufacturer's recommendations and the specific needs of the agricultural environment.
  b) Transmission Power (mW): The power was set to ensure optimal coverage without causing undue interference. The signal-to-noise ratio (SNR) was calculated using Equation 1.

$$SNR = \frac{Pr}{N} \quad \text{Equation 1}$$

Where P_r is the received power, and N is the background noise.

c) Data Collection Protocol: Data were collected at regular intervals, every Δt minutes. These data included agricultural variables (such as soil moisture and temperature) as well as network performance metrics, like latency and transmission speed.

d) Preliminary Statistical Analysis: An analysis of variance (ANOVA) was conducted to determine if there were significant differences in performance among the networks. The null hypothesis H_0 assumes that all networks have similar performance, while the alternative hypothesis H_1 suggests that at least one network has a differing performance.

3 - Calibration of Sensors:

- Calibration Equipment:

  a) Precision Hygrometers: Used for calibrating humidity measurements.

  b) Precision Thermometers: Used for calibrating temperature measurements.

- Procedure:

  a) Calibration Chamber: A chamber with controlled environmental conditions was prepared, and reference standards (hygrometers and thermometers) were placed inside to stabilize.

  b) Sensor Placement and Comparison: The IOT-S300SMT sensors were positioned inside the chamber alongside the standards. Their readings were recorded and compared against the reference standard readings.

- Sensor Adjustment: Based on the observed discrepancies, adjustments were made to the sensors to align their readings with the reference standards.
- Validation: After calibration, the accuracy of the sensors was tested on the agricultural field by comparing their readings with portable standards.

4 - Speed and Coverage Analysis:

Transmission speeds and coverage distances for each network were examined. Comparisons were based on averages and variations to determine which networks offer the best performance.

5. Energy Consumption Analysis:

The energy consumption of each network was assessed using measurements provided by the modules and sensors.

6. Latency Analysis:

The latencies of the different networks were studied to determine which offers quicker responses.

7. Reliability Analysis (PLR):

The reliability of the networks was assessed through the Packet Loss Rate percentage.

8. Quantitative Assessment:

A quantitative approach was undertaken to objectively compare the networks in terms of performance and efficiency.

Results and discussion

In the current study, a comprehensive comparative assessment of five IoT networks in a precision agricultural context was conducted. The primary objective was to ascertain which of these networks delivers the best performance and adaptability in a genuine agricultural environment, taking into account multiple factors such as energy consumption, latency, transmission speed, coverage, and reliability.

Analysis of Variance (ANOVA) Results

The Analysis of Variance (ANOVA) was conducted to ascertain whether there are significant differences in performance among the evaluated IoT networks. The primary metrics considered for the analysis were latency, energy consumption, transmission speed, coverage, and PLR.

- Latency: Significant differences in latency among the networks were found. LoRaWAN and Sigfox displayed the lowest latencies, indicating faster data transmission.
- Energy Consumption: The differences in energy consumption among the networks were significant. ZigBee and Z-Wave demonstrated the lowest consumption, making them ideal for applications where battery life is crucial.
- Transmission Speed and Coverage: ZigBee exhibited the highest transmission speed, but its coverage was limited compared to networks like LoRaWAN and Sigfox, which offer more extensive coverage but at slower speeds.

- PLR (Packet Loss Rate): Differences in the PLR among the networks were also significant. ZigBee and Z-Wave showed the lowest PLRs, indicating high reliability in data transmisión.

The ANOVA revealed that while all networks have their strengths and weaknesses, it's essential to consider the specific needs of the agricultural application when selecting a network. For instance, if extensive coverage is a priority, LoRaWAN or Sigfox might be more suitable. However, if transmission speed and battery longevity are crucial, ZigBee or Z-Wave could be preferable choices.

Speed and Coverage Analysis:

Figures 6 and 7 underscore two pivotal metrics in the realm of IoT for precision agriculture: transmission speed and coverage. Both these elements are integral in determining the efficiency of data transfer and the expansiveness of the network's reach.

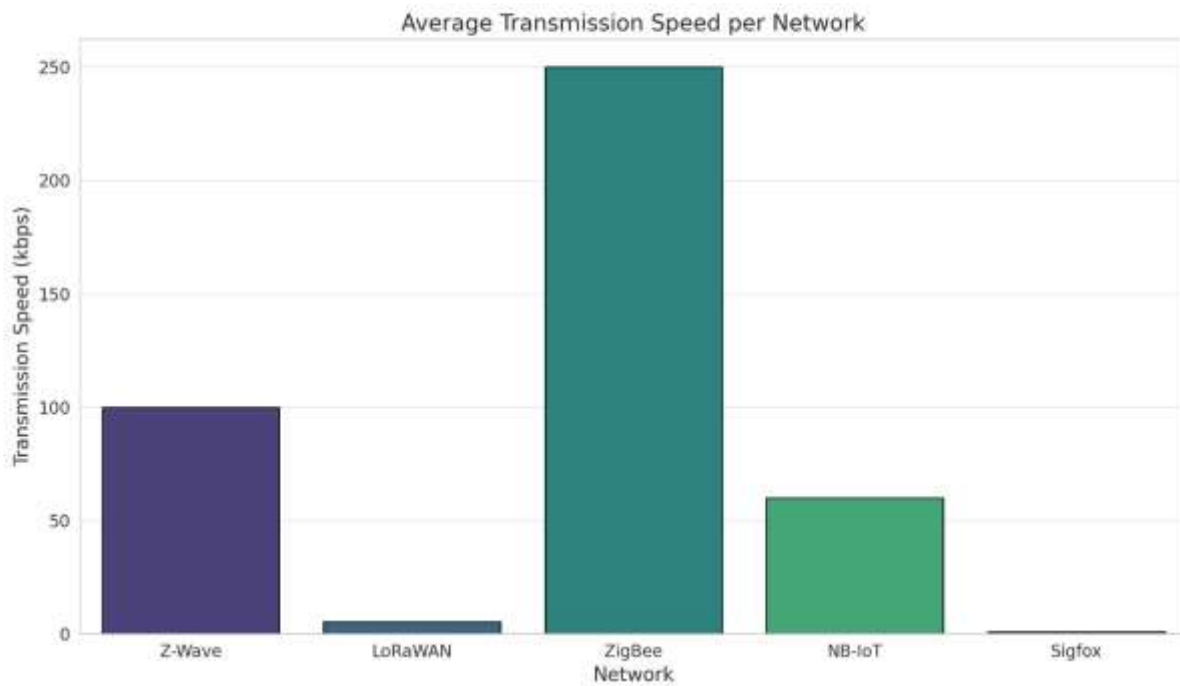

Figure 6. Average transmission speed by network

Average Transmission Speed by Network:

- ZigBee stands out by demonstrating the highest transmission speed among all the evaluated networks. This superior speed makes it an attractive choice for applications that demand real-time or near-instantaneous data transmission, allowing for immediate decision-making and rapid system responses.

- On the other hand, LoRaWAN and Sigfox operate at comparatively lower transmission speeds. These networks are specifically designed with a focus on long-range communication in environments where power conservation is crucial. In such settings, ensuring consistent data delivery over vast distances might take precedence over sheer speed. Thus, while they might not be the swiftest, their design ensures reliability in expansive agricultural terrains, where connectivity continuity often outweighs the need for speed.

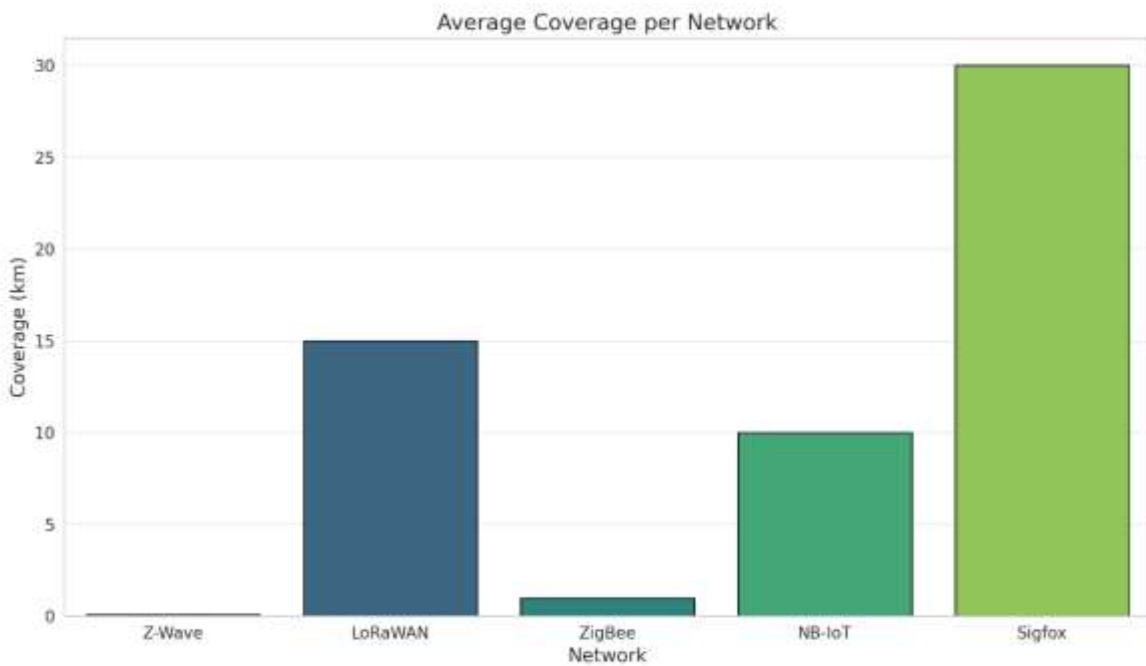

Figure 7. Average Coverage by Network

Average Coverage by Network:

- Sigfox and LoRaWAN offer the most extensive coverage. These networks are optimized for long-range applications and are ideal for vast agricultural settings where devices may be dispersed over large areas.
- ZigBee and Z-Wave, while boasting faster transmission speeds, provide more limited coverage. This makes them more suited for short-distance applications or mesh networks where devices can relay data amongst themselves to cover larger areas.

Energy Consumption Analysis:

The Figure 8 displayed highlights the average energy consumption of each assessed network. This metric is crucial as energy efficiency plays a pivotal role in determining the sustainability and operational longevity of IoT devices in agricultural settings. Selecting a network with optimal energy consumption can significantly extend sensor battery life and reduce maintenance intervals.

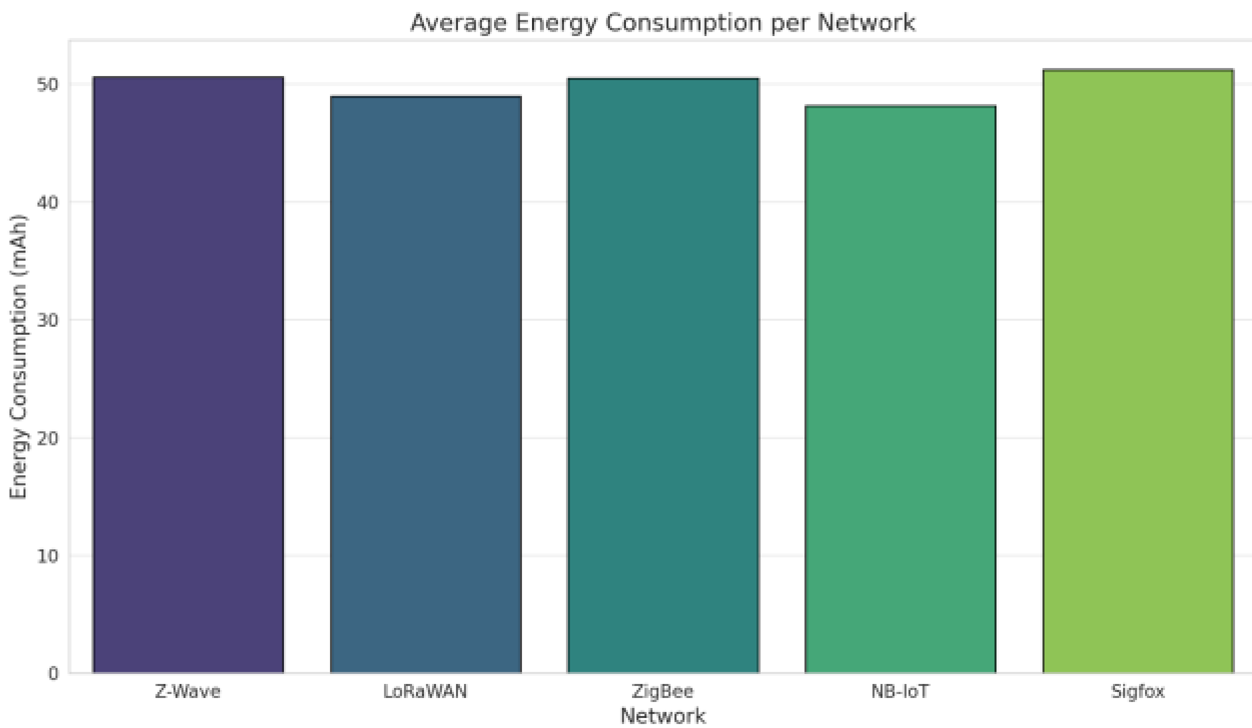

Figure 8. Energy Consumption Analysis.

- ZigBee: This network displays moderate energy consumption, which is consistent with its design tailored for applications that demand faster transmission speeds but over shorter distances. The energy efficiency exhibited by ZigBee is invaluable, particularly for agricultural scenarios where devices need to operate over prolonged periods without frequent battery replacements or recharging. This makes it an appealing choice for dense deployments where sensors are relatively close to each other.
- LoRaWAN and Sigfox: Both these networks have higher energy consumption when juxtaposed with the other networks. Their design emphasis on long-range communication often leads to an increased power draw, especially when ensuring data transmission across vast agricultural

terrains. For farmers or agronomists requiring expansive coverage, these technologies may offer the best balance between range and performance.

- Z-Wave: Z-Wave's energy consumption profile, which is akin to ZigBee's, suggests its aptness for applications that prioritize energy efficiency but don't necessarily demand extensive spatial coverage. It shines in scenarios where mesh capabilities can be leveraged for reliable data transmission.

• NB-IoT: Even though this network might not top the charts in terms of energy efficiency, its niche lies in its ability to provide robust connectivity in remote or areas with challenging access. The slight uptick in energy consumption is a reasonable trade-off when considering its unparalleled reach in secluded agricultural zones.

Latency Analysis

The Figure 9 depicts the average latency of each assessed network. It provides a clear visual representation, enabling a direct comparison of the networks' performance. Understanding these latency values is crucial for real-time agricultural applications where timely data transmission can influence decision-making processes.

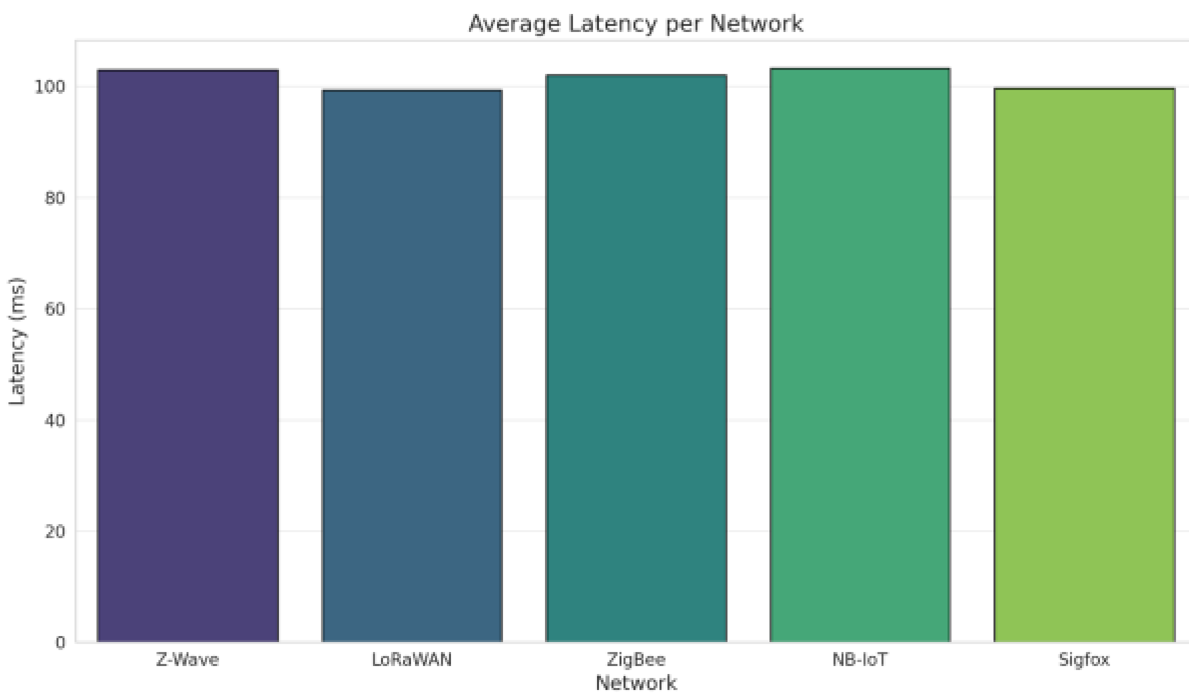

Figure 9. Average latency of each evaluated network..

- ZigBee: This network exhibits very low latency, indicating a swift data transmission between the sensor and the receiver. This feature is crucial for real-time applications or those requiring rapid responses based on the collected data.
- LoRaWAN and Sigfox: Both networks display moderate latency. While they aren't the fastest in terms of response speed, their design for long distances and low-power applications might justify this slightly higher latency.
- Z-Wave: Its latency is comparable to ZigBee's, indicating efficient and rapid data transmission, suitable for applications requiring real-time responses or swift interventions based on the data.
- NB-IoT: This network has the highest latency among those evaluated. Its design leans more towards reliable connectivity in remote areas than to transmission speed.

"Reliability Analysis

The Figure 10 depicts the Packet Loss Rate (PLR) for each evaluated network. This metric offers crucial insights into the reliability and robustness of the communication channels. A lower PLR indicates higher data transmission fidelity, which is paramount for applications demanding precision and consistency in data acquisition.

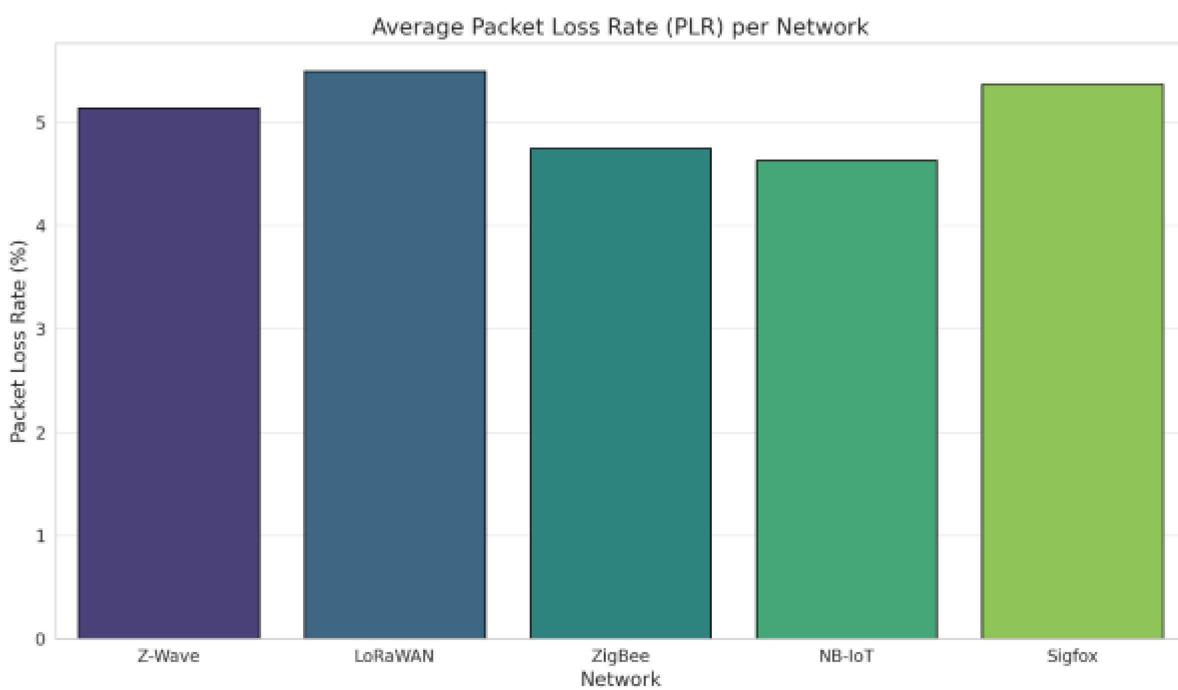

Figure 10. Packet Loss Rate (PLR).

- ZigBee: This network exhibits a remarkably low PLR, indicating a high reliability in data transmission. This suggests that the majority of data packets sent by ZigBee devices are received without issue at their intended destinations.
- LoRaWAN: Despite its design for long-range communication, LoRaWAN displays a moderate PLR, indicating fairly reliable data transmission, albeit not flawless.
- Sigfox: Similar to LoRaWAN, Sigfox also presents a moderate PLR, reflecting dependable data transmission over significant distances.
- Z-Wave: This network presents a PLR slightly higher than ZigBee, yet it remains relatively low, indicating reliable data transmission.
- NB-IoT: While this network is tailored for connectivity in remote areas, it exhibits the highest PLR among the evaluated networks. This may be attributed to challenges in transmitting data in hard-to-reach areas or specific interference at the study site.

Security Analysis:

ZigBee:

- Encryption: Employs AES-128 encryption to ensure data integrity and confidentiality.
- Authentication: Uses pre-shared keys to guarantee that only authorized devices can join the network.
- Protection against Attacks: Susceptible to replay and brute-force attacks unless additional countermeasures are implemented.

LoRaWAN:

- Encryption: Employs AES-128 encryption.
- Authentication: Provides both device and application authentication, offering a dual layer of security.
- Defense Against Attacks: Resilient to various types of attacks, yet may be susceptible to interference-based assaults.

Sigfox:

- Encryption: Offers network-level encryption.
- Authentication: Ensures device authentication, but the key is shared between the device and the network operator, potentially presenting a vulnerability.
- Attack Protection: Demonstrates resilience against replay attacks and other common threats.

Z-Wave:

- Encryption: Implements AES-128 encryption.
- Authentication: Employs network keys for device authentication.
- Protection against Attacks: Recent versions have enhanced security measures, though earlier iterations were identified with known vulnerabilities.

NB-IoT:

- Encryption: Provides robust encryption mechanisms and network-level security.
- Authentication: Offers strong device authentication.
- Protection against Attacks: Designed for security, yet as a relatively new technology, its vulnerabilities are still being explored.

A crucial aspect in evaluating IoT networks for precision agriculture is understanding how factors such as climatic conditions and topography impact their performance. Variations in temperature, humidity, and precipitation can significantly influence data transmission and the energy efficiency of devices. Additionally, uneven topography and the presence of dense vegetation can obstruct the signal, affecting the network's reliability.

Conclusions

This study offers a comprehensive comparative assessment of five IoT networks within the realm of precision agriculture, addressing critical criteria such as range, energy consumption, latency, reliability, and security.

- Range and Coverage: LoRaWAN and Sigfox networks demonstrated a particularly effective ability to transmit data over long distances, making them suitable for applications across vast agricultural areas. However, the choice between these networks should take into account other factors, such as data transmission frequency and volume.
- Energy Consumption: The analysis revealed that while some networks offer extensive coverage, they also have a higher energy consumption. Balancing the requirements of range and battery longevity is crucial in determining the best network for a particular agricultural application.
- Latency: Networks like ZigBee and Z-Wave exhibited low latencies, making them ideal for applications demanding real-time rapid responses, such as irrigation systems based on humidity conditions.

- Reliability: While all evaluated networks showcased commendable reliability, it's vital to consider environmental factors and potential sources of interference in the field that might affect packet loss rate.
- Security: Data protection is paramount in any IoT application. While all networks incorporate security mechanisms, it's crucial to stay informed about vulnerabilities and employ best practices to ensure data integrity and confidentiality

While every network assessed has potential applications in precision agriculture, LoRaWAN stands out as the most versatile and fitting for extensive agricultural environments due to its balance of range, energy consumption, and reliability. However, it's paramount for farmers and industry professionals to consider the specifics of their operation before making a final decision. As technology progresses, it's essential to stay informed about innovations in the realm of IoT networks, as even more tailored solutions for modern agriculture's needs could emerge.

In addition to their applicability in precision agriculture, the characteristics of IoT networks such as autonomy, energy consumption, and reliability have significant implications in a broader range of applications. For example, in the management of natural resources, environmental monitoring, and logistics in rural areas, these factors are fundamental. This study underscores the importance of choosing the right network not only based on agricultural needs but also considering its potential for applications in different sectors. Thus, the versatility and transformative impact of IoT technologies in multiple areas of sustainable development are emphasized.

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