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IoT Communication Technologies for Agricultural Monitoring System

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***Abstract* - Modern agricultural monitoring systems are essential for transitioning from traditional practices to data-driven methods that address global food demand and climate change. This research examines various IoT communication technologies, evaluating their performance based on range, power consumption, scalability, and cost. The paper reviews short-range technologies like Wi-Fi and ZigBee, noting their high data rates but limited coverage, alongside long-range LPWAN solutions such as LoRa, NB-IoT, and Sigfox. By integrating these technologies with sensors and cloud platforms, farmers can achieve real-time monitoring of environmental parameters like soil moisture and temperature.**

The study highlights that while short-range options are effective for small-scale cultivation, LPWAN technologies provide the efficiency required for large-area monitoring. Ultimately, this review identifies the most effective communication frameworks to support automated irrigation and remote decision-making. Such advancements contribute to the development of smarter, more resilient and sustainable farming systems in the era of Agriculture 4.0. This comprehensive analysis provides a foundational guide for selecting optimal connectivity solutions to enhance overall agricultural efficiency.

Keywords: LORA, Wi-Fi, Sigfox, NBA IoT, Zigbee, agriculture monitoring.

I. INTRODUCTION

Agriculture monitoring systems are technological solutions that continuously observe, collect and analyze factors such as soil moisture, temperature, humidity and crop health in real-time. Previously, farming dependent on manual observation and decisions based on experience, often leading to inaccuracy and inefficiency. Modern monitoring systems use sensors, data processing units, and communication networks to automate these tasks. This allows precise and timely decision making to be performed. These systems are essential for smart agriculture, transforming traditional farming into data-driven methods that improve productivity and resource use.

The need for agriculture monitoring systems has grown owing to the increasing global demand for food, climate change, and the necessity for sustainable resource management. With the world population expected to rise quickly, agricultural systems must generate more output using limited resources such as water and soil nutrients. Traditional practices have also led to environmental issues such as soil depletion and high-water usage. Monitoring systems help to tackle these problems by promoting efficient irrigation, early disease detection, and optimized fertilizer use, thus boosting productivity and sustainability.

To support this monitoring different communication technologies are used to send data from the field sensors to central systems. Older technologies such as Wi-Fi, Zigbee and Bluetooth were popular because of their low cost and easy deployment, however they have drawbacks such as short communication ranges and higher power consumption. For example, Wi-Fi usually covers only a few meters of distance, making it impractical for large areas. To address these issues newer technologies such as low-power wide-area networks (LPWAN), including LoRa, NB-IoT and Sigfox have been developed. These technologies offer a long-range communication, low power use, and affordable data transmission, making them ideal for agricultural monitoring applications.

In this regard, the Internet of Things (IoT) is a key technology that links physical agricultural devices to the digital world. The IoT is a network of connected devices with sensors, software and communication functions that gather and share data over the internet. In agriculture, the IoT enables real-time of environmental and crop conditions, producing large amount of data for better decision-making. This marks a shift toward Agriculture 4.0 where farming becomes more automated, efficient and data-focused.

Communication technologies are vital to IoT-based agricultural systems because they enable smooth data transfer

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between sensors, gateways, cloud platforms and users in these systems. These technologies ensure liable data transmission from distributed sensor nodes across large farm areas to the cloud. For example, LoRa can transmit data over several kilometers using minimal power, whereas Wi-Fi and cellular networks connect to cloud platforms for data storage and analysis. Integrating these technologies into IoT systems allows for ongoing monitoring, remote access and real-time support for farmers.

IoT based agriculture also called as smart agriculture, uses these communication technologies, alongside sensors and cloud computing to improve farming practices. It supports automated irrigation systems, climate monitoring, crop analysis and preventive maintenance of the equipment. By using real-time data and advanced analytics, IoT boosts crop yield, lowers operational costs and reduces environmental impact. Additionally, it aids precision agriculture by allowing farmers to make specific decisions based on location, thereby enhancing overall efficiency and sustainability.

This review examines various IoT communication technologies in agricultural monitoring systems, focusing on their advantages, limitations and use in different farming situations. It provides an overview of existing technologies such as Wi-Fi, Zigbee, Bluetooth, LoRa and other LPWAN solutions assessing their performance in terms of range, power consumption, scalability and cost. The goal is to identify the use of these merits and demerits for effective and sustainable agricultural monitoring thereby helping to develop smarter and more resilient farming systems.

II. IOT TECHNOLOGIES FOR AGRICULTURE

2.1 Wi-Fi

Wi-Fi based on the IEEE 802.11 standard is one of the most widely used wireless communication technologies in Internet of Things (IoT)-based agricultural monitoring systems due to its high data transmission rate, widespread availability, and ease of deployment. Operating in the 2.4 GHz and 5 GHz frequency bands, it typically provides a communication range of 50-100 m, making it suitable for greenhouses and small-scale farms that require real-time monitoring. Wi-Fi enables reliable Machine-to-Machine (M2M) communication between IoT devices, cloud platforms and users, thereby supporting efficient precision agriculture applications. Feng et al. reported that Wi-Fi is particularly effective for greenhouse monitoring because of its high throughput and reliable connectivity, although its performance decreases in large agricultural fields due to limited coverage. [1], [8].

In a typical Wi-Fi based agricultural monitoring system as shown in Fig. 1, sensors measure environmental parameters such as soil moisture, temperature, humidity, water level and pH and transmit the collected data through an ESP8266 Wi-Fi module to a wireless router. The router uploads the data to cloud platforms such as ThingSpeak, allowing farmers to remotely monitor field conditions and make informed irrigation and crop management decisions.

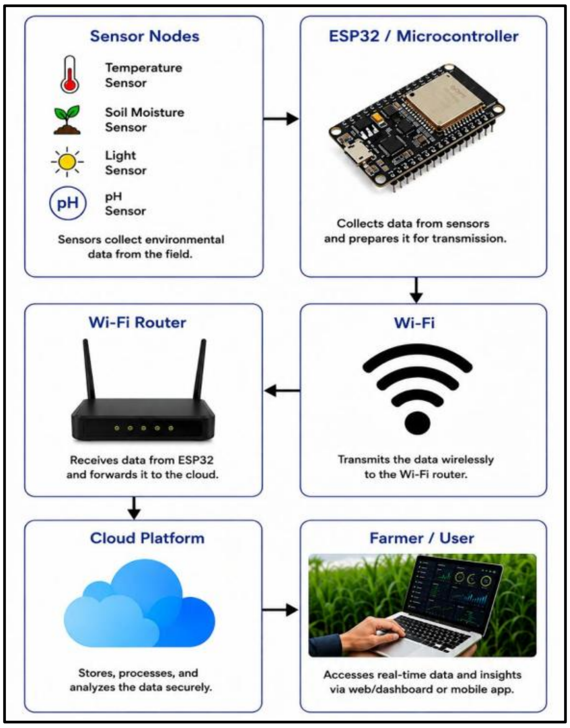

Figure 1: Architecture of Wi-Fi Based Agriculture Monitoring System

An IoT-based monitoring system using ESP8266 and ThingSpeak successfully enabled remote monitoring of soil moisture, temperature, humidity and water level for efficient irrigation management. Similarly, Tang *et al.* reviewed Wi-Fi based smart irrigation systems that monitored environmental parameters such as soil moisture, rainfall, salinity and pH improving water-use efficiency through real-time cloud connectivity. These studies highlight Wi-Fi as a reliable communication technology for agricultural applications requiring continuous Internet access and rapid data transmission [2], [11].

Despite its advantages, Wi-Fi has limitations, including high power consumption, limited communication range and reduced scalability in large agricultural fields due to increased network congestion. Therefore, Wi-Fi is best suited for greenhouses, smart irrigation systems, and small farms [1],[2].

2.2 Zigbee (IEEE 802.15.4)

ZigBee, based on the IEEE 802.15.4 standard is a low-power and low-data rate wireless communication technology widely used in Internet of Things (IoT) based agricultural

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monitoring systems. It primarily operates in the range 2.4 GHz ISM band worldwide with optional operation at 868 MHz and 915 MHz, offering a communication range of approximately 10-100 m depending on the deployment environment. Although its data rate is relatively low (up to 250 kbps), ZigBee is highly suitable for agricultural applications because of its low energy consumption, low deployment cost, and ability to support a large number of interconnected sensor nodes through mesh networking. ZigBee based wireless sensor networks provide an efficient solution for precision agriculture by enabling reliable communication between distributed sensor nodes while minimizing power consumption. Furthermore, comparative studies have identified ZigBee as one of the most suitable wireless communication technologies for greenhouse monitoring because of its balance between communication range and energy efficiency [1], [3].

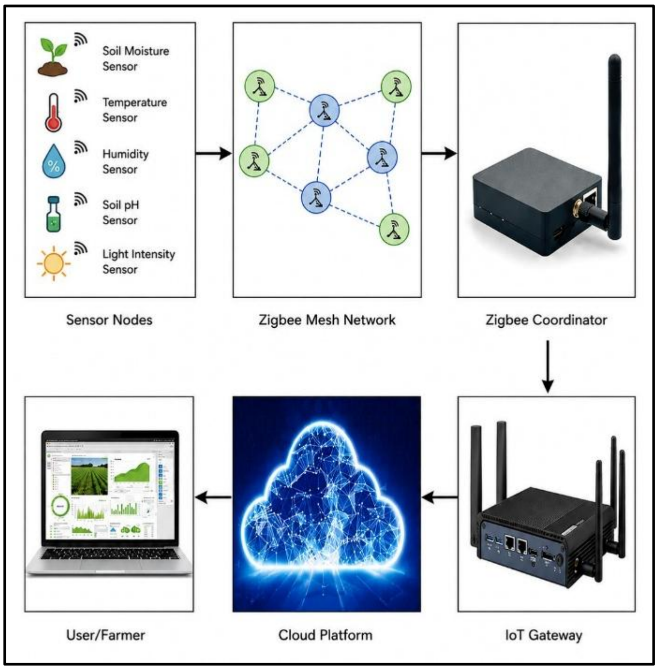

Figure 2: Architecture of Zigbee Based Agriculture Monitoring System

In a typical ZigBee based agricultural monitoring system as shown in Fig. 2, environmental sensors continuously measure parameters such as soil moisture, temperature, humidity, soil pH and light intensity and transmit the collected data to nearby ZigBee sensor nodes. These nodes communicate through a mesh network, where routers relay the information to a ZigBee coordinator, which forwards the aggregated data to an IoT gateway or cloud platform. Farmers can then access real-time field information through computers or mobile devices, enabling timely irrigation scheduling and crop management decisions. The mesh topology improves communication reliability by providing multiple transmission paths and maintaining network connectivity even when individual nodes fail [3], [4].

Several studies have demonstrated the practical application of ZigBee in the smart agriculture. ZigBee based wireless sensor networks have been successfully implemented for monitoring environmental parameters while reducing energy consumption. Comparative analyses have shown that ZigBee is particularly suitable for facility agriculture and greenhouse environments because of its low power consumption and reliable short-range communication. More recently, an improved ZigBee routing protocol (EMP-ZBR) for greenhouse monitoring significantly reduced network delay, improved packet delivery and minimized routing overhead by optimizing the mesh network topology. These findings demonstrate that ZigBee provides reliable and energy-efficient communication for agricultural monitoring systems deployed over small and medium-sized cultivation areas [1], [3], [4].

Despite these advantages, ZigBee has a certain limitation. Its short communication range, low data rate and the requirement for multiple relay nodes in large agricultural fields reduces its scalability for wide-area deployments [1], [4].

2.3 LoRa - Long Range

LoRa (Long Range) is a Low-Power Wide-Area Network (LPWAN) communication technology specifically designed for long-distance, low-power IoT applications. It operates in the license-free Industrial Scientific and medical (ISM) frequency bands, including 433 MHz, 868 MHz and 915 MHz depending on regional regulations. LoRa supports communication ranges of 2-15 km in rural environments and provides a data rate ranging from 0.3 kbps to 50 kbps, making it highly suitable for agricultural monitoring applications that require periodic transmission of small amount of sensor data. Unlike conventional wireless technologies, LoRa employs Chirp Spread Spectrum (CSS) modulation which improves communication reliability while maintaining very low power consumption. Owing to its long communication range, low deployment cost and extended battery life of up to several years, LoRa has become one of the most widely adopted communication technologies for precision agriculture and smart farming applications [1], [5].

In a typical LoRa-based agricultural monitoring system as shown in Fig. 3, environmental sensors continuously measure the parameters such as soil moisture, temperature, humidity, air quality, and light intensity. The sensed data are processed by a microcontroller such as ESP32 or Arduino, which transmits the information through a LoRa trans receiver to a LoRa gateway. The gateway forwards the collected data through the Internet to a network server and cloud platform, enabling farmers to monitor field conditions remotely using

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smartphones or computers. This communication architecture allows reliable real-time monitoring over large agricultural fields while minimizing energy consumption and infrastructure requirements [2], [5].

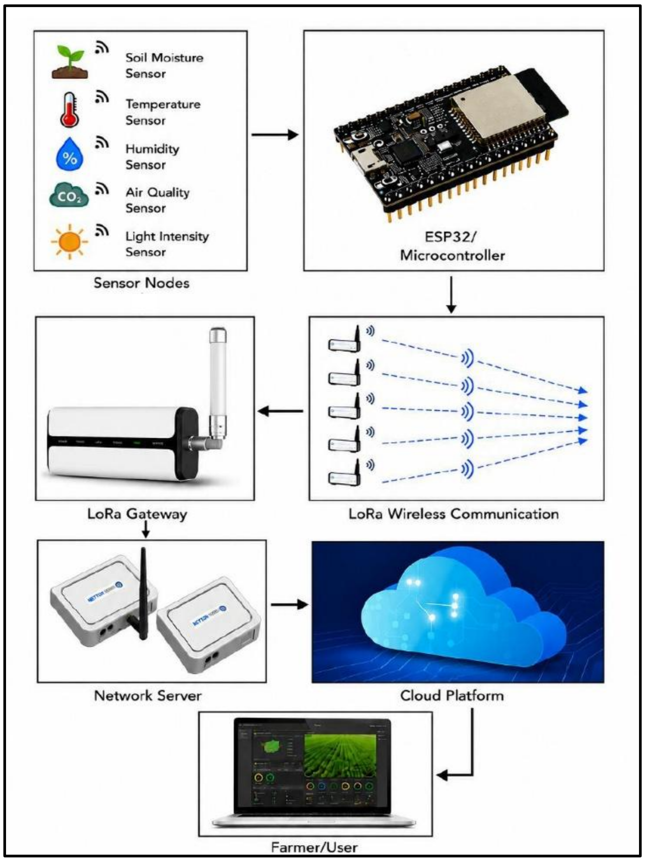

Figure 3: Architecture of LoRa Based Agriculture Monitoring System

Several studies have demonstrated the effectiveness of LoRa in agricultural monitoring systems. Pagano et al. reviewed numerous LoRa based applications including irrigation systems, crop monitoring, tree monitoring and livestock monitoring and concluded that LoRa provides excellent scalability, energy efficiency and wide area coverage for smart agriculture. Feng et al. compared LoRa with ZigBee and NB-IoT and reported that LoRa is the most suitable technology for large-scale field agriculture because of its long communication range and low power consumption. Furthermore, Tang et al. reviewed several LoRa-based irrigation systems where soil moisture, temperature, humidity and environmental parameters were transmitted to the cloud platforms resulting in improved irrigation efficiency and reduced water consumption. Recent studies have also highlighted that LoRa WAN offers secure communication simplified network deployment and cost effective monitoring for remote agricultural environments [1], [2], [5], [6].

Despite these advantages, Lora has certain limitations, its low data rate makes it unsuitable for transmitting multimedia data such as images or videos, while duty-cycle regulations restrict continuous communication. Additionally, increased network density may lead to packet collisions and communication delays. Nevertheless, LoRa remains one of the most appropriate communication technologies for large-scale agricultural monitoring, precision farming and smart irrigation systems where long communication range, low energy consumption and extended battery life are the primary requirements [1], [2], [5], [6].

2.4 NB-IoT - Narrowband Internet of Things

NB-IoT (Narrowband Internet of Things) is a 3GPP release 13 standardized Low-Power Wide-Area Network (LPWAN) technology developed to provide reliable, low-power and wide-area connectivity for Internet of Things (IoT) applications. Unlike Wi-Fi and ZigBee NB-IoT operates over licensed LTE cellular frequency bands using a narrow bandwidth of 180-200 kHz, providing communication coverage of up to 10-15 km in rural environments while supporting data rates of approximately 20-250 kbps depending on network configuration. Its excellent coverage, high connection density and long battery life make NB-IoT a suitable communication technology for agricultural monitoring systems is unavailable. Furthermore, its operation over existing cellular infrastructure eliminates the need for dedicated gateways, simplifying large-scale agricultural deployments [1], [7].

In a typical NB-IoT based agricultural monitoring system as shown in Fig. 4, environmental sensors continuously monitor parameters such as soil moisture, soil temperature, air temperature, humidity, water level, pH and light intensity. The collected data are processed by a microcontroller such as ESP32 or Arduino and transmitted through an NB-IoT communication module to the nearest cellular base station. The cellular network forwards the information an IoT cloud platform where the data are stored, analyzed and visualized. Farmers can then remotely access real-time field information using smartphones or computers, enabling timely irrigation scheduling, crop management and resource optimization [2], [7].

Several studies have demonstrated the effectiveness of NB-IoT in smart agriculture. Comparative studies have shown that NB-IoT provides better communication reliability and wider coverage than short-range technologies such as Wi-Fi and ZigBee making it particularly suitable for large-scale agricultural fields. Agricultural irrigation systems employing NB-IoT have successfully monitored soil moisture, temperature, humidity, water level and crop conditions enabling intelligent irrigation management while improving water-use efficiency. In addition, recent surveys have

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identified NB-IoT as one of the most promising LPWAN technologies for precision agriculture because of its secure cellular communication, low maintenance requirements and ability to support thousands of connected devices within a single network [1], [2], [8].

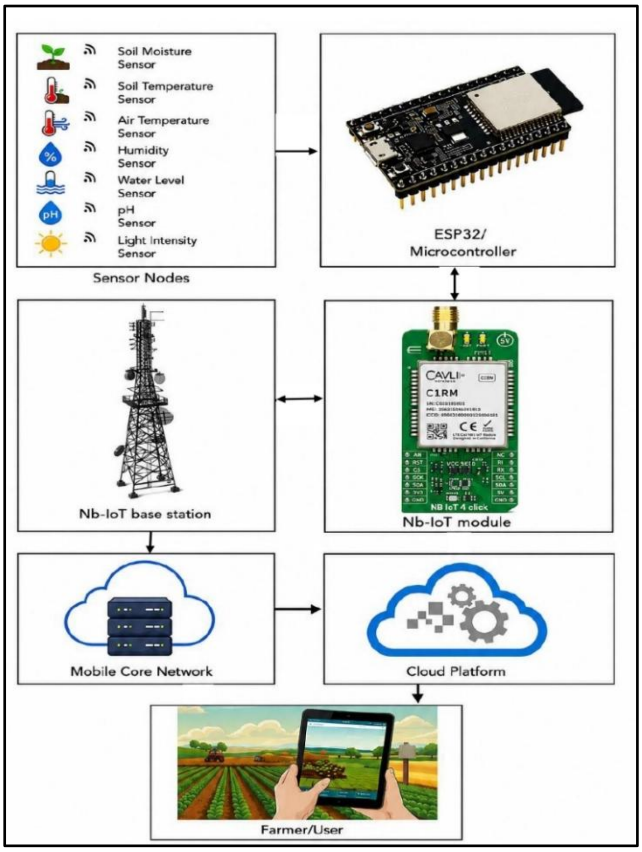

Figure 4: Architecture of Nb-IoT Based Agriculture Monitoring System

Despite these advantages, NB-IoT has several limitations. Since it relies on cellular network infrastructure, its performance depends on network availability and operator coverage. Moreover, subscription costs, higher communication latency than Wi-Fi and relatively low data rates make it unsuitable for bandwidth-intensive applications such as image or video transmission. Nevertheless NB-IoT remains an excellent choice for large-scale agricultural monitoring, smart irrigation and remote farming applications where long consumption is more important than high-speed data transmission [1], [2], [7], [8].

2.5 Sigfox

Sigfox is a Low-Power Wide-Area Network (LPWAN) communication technology designed for IoT applications that require ultra-low power consumption, long-range communication and the transmission of small amounts of data. Unlike Wi-Fi and ZigBee, Sigfox operates in the license-free Industrial Scientific and Medical (ISM) frequency bands such as 868 MHz in Europe and 902 MHz in North America, using Ultra-narrow Band (UNB) modulation to achieve high communication reliability with minimal energy consumption. It typically provides communication ranges of 10-50 km in rural environments while supporting a very low data rate of approximately 100 bps with a maximum payload of 122 bytes per uplink message. Owing to its long battery life simple network architecture and low deployment cost, Sigfox is considered a suitable communication technology for agricultural monitoring systems that periodically transmit small sensor readings over large geographical areas [8], [9], [10].

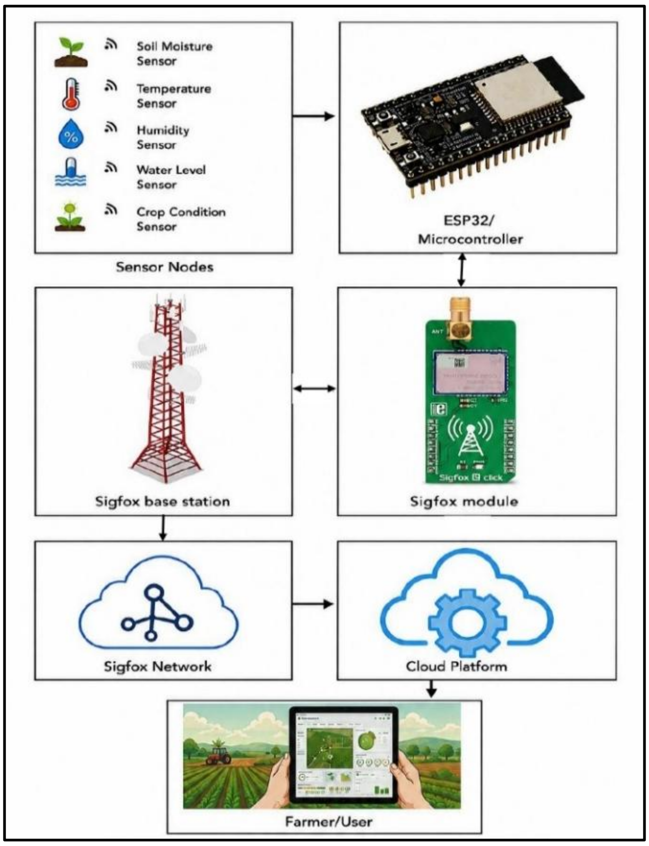

Figure 5: Architecture of Sigfox Based Agriculture Monitoring System

In a typical Sigfox-based agricultural monitoring system as shown in Fig. 5, environmental sensors continuously measure parameters such as soil moisture, temperature, humidity, water level and crop conditions. The collected data are processed by a microcontroller such as ESP32 or Arduino and transmitted through a Sigfox communication module to the nearest Sigfox base station. The base station forwards the received information to the Sigfox cloud platform, where the data are stored and processed before being accessed by farmers through web or mobile applications. Since only small sensor packets are transmitted at regular intervals, the system achieves very low energy consumption while providing reliable long-distance monitoring suitable for remote agricultural environments [2], [8].

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Table 1: Comparison of IoT Communication Technologies

Parameter	Wi-Fi	ZigBee	LoRa	NB-IoT	Sigfox
Standard	IEEE 802.11	IEEE 802.15.4	LoRa WAN (LoRa Alliance)	3GPP Release 13	Sigfox UNB Protocol
Frequency Band	2.4 GHz, 5 GHz	2.4 GHz, 868/915 MHz	433, 868, 915 MHz (ISM)	Licensed LTE Band (180–200 kHz)	868 MHz (EU), 902 MHz (US)
Communication Range	50–100 m	10–100 m	2–15 km	1–15 km	10–50 km
Data Rate	Up to 600 Mbps	Up to 250 kbps	0.3–50 kbps	20–250 kbps	~100 bps
Power Consumption	High	Low	Very Low	Low	Very Low
Battery Life	Hours to days	Months to years	5–10 years	5–10 years	Up to 10 years
Network Topology	Star	Star / Mesh / Tree	Star (via Gateway)	Cellular (Star)	Star
Coverage Type	Local Area Network (LAN)	Personal Area Network (PAN)	Low-Power Wide Area Network (LPWAN)	Cellular LPWAN	Low-Power Wide Area Network (LPWAN)
Infrastructure Required	Wi-Fi Router / Access Point	ZigBee Coordinator & Routers	LoRa Gateway	Cellular Base Station	Sigfox Base Station
Internet Connectivity	Direct	Through Gateway	Through Gateway	Direct via Cellular Network	Direct via Sigfox Network
Scalability	Moderate	High	Very High	Very High	High
Deployment Cost	Low	Low	Medium	Medium–High	Medium
Operational Cost	Low	Low	Low	Subscription Required	Subscription Required
Advantages	High speed, easy Internet access, real-time communication	Low power consumption, mesh networking, low cost	Long communication range, low power consumption, long battery life	Wide coverage, reliable cellular connectivity, good scalability	Ultra-low power consumption, long range, extended battery life
Limitations	High power consumption, limited communication range, poor scalability	Short communication range, low data rate	Low data rate, duty-cycle limitations	Cellular dependency, subscription cost	Very low data rate, limited payload size

Despite these advantages, Sigfox has several limitations. It’s very low data rate, small payload size and dependence on existing Sigfox network coverage restrict its flexibility in many agricultural deployments. Furthermore, users cannot establish private Sigfox networks, making its adoption dependent on the availability of commercial infrastructure. Nevertheless, Sigfox remains a practical solution for remote agricultural monitoring, livestock tracking and low-frequency environmental sensing where ultra-low power consumption, long communication range and extended battery life are the primary requirements. [2], [8], [9], [10].

2.6 Comparison of IoT Technologies

The Table 1 gives the comparison of different IoT technologies. The selection of an optimal Internet of Things (IoT) communication protocol for agricultural monitoring systems involves balancing distinct technical trade-offs regarding range, power longevity, and throughput. Short-range technologies like Wi-Fi and ZigBee operate within localized contexts, offering high data rates—up to 600 Mbps and 250 kbps respectively—but they are restricted by limited coverage areas and, in the case of Wi-Fi, substantial power consumption. Conversely, Low-Power Wide-Area Networks

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(LPWANs), including LoRa, NB-IoT, and Sigfox, are structurally optimized for expansive agricultural landscapes due to their extensive communication ranges stretching up to 15 to 50 kilometers. These LPWAN frameworks exhibit exceptional energy efficiency, yielding battery lifespans of 5 to 10 years, though they trade off high throughput for lower data rates ranging from a sparse 100 bps to 250 kbps. Financially, deployment frameworks vary; while Wi-Fi and ZigBee benefit from low operational costs, cellular-dependent solutions like NB-IoT require ongoing subscription fees but guarantee high scalability and reliable connectivity. Ultimately, deploying these technologies requires a strategic alignment with specific farm topologies, balancing the need for real-time high-bandwidth data against wide-area, low-power telemetry.

III. CONCLUSION

Among the reviewed communication technologies, Wi-Fi provides the highest data rate and is well suited for greenhouse monitoring and small farms. ZigBee offers lower power consumption and mesh networking making it appropriate for short-range sensor networks. LoRa provides an excellent balance between communication range and energy efficiency making it one of the most suitable technologies for large-scale agricultural monitoring. NB-IoT offers reliable wide-area coverage through existing cellular infrastructure but incurs subscription costs. Sigfox provides ultra-low power consumption and long battery life but is limited by its very low data rate and small payload size. Therefore, the choice of communication technology depends on the application's coverage, energy, data rate and cost requirements.

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