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Review

Application of Internet-of-Things Wireless Communication Technology in Agricultural Irrigation Management: A Review

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Abstract: The integration of Internet-of-Things technology with traditional agricultural irrigation is a crucial factor in the advancement of traditional agricultural irrigation towards smart irrigation. Despite the widespread use of conventional irrigation methods in many areas, they lead to the significant wastage of both human and water resources. Therefore, the development of energy-saving and efficient intelligent irrigation systems through the application of Internet-of-Things technology and wireless communication technology is the way forward. This paper summarizes the common wireless communication technologies in the agricultural Internet of Things: Fifth-generation, WiFi, ZigBee, LoRa, and NB-IoT. The research status of the above wireless communication technology in agricultural irrigation management is discussed, and the agricultural irrigation management example using the above wireless communication technology is also presented. The advantages and limitations of the application of the above wireless communication technology in agricultural irrigation management are sorted out. Finally, this paper analyzes the challenges of data security issues, data fusion problems, intelligent irrigation system costs, power and energy problems, and system equipment failures faced by the use of IoT wireless communication technology in agricultural irrigation management. This review aims to assist researchers and users in choosing the most suitable wireless communication technology for diverse applications.

Keywords: agricultural irrigation management; Internet of Things; LoRa; wireless communication technology; Fifth-generation

Citation: Tang, P.; Liang, Q.; Li, H.; Pang, Y. Application of Internet-of-Things Wireless Communication Technology in Agricultural Irrigation Management: A Review. *Sustainability* **2024**, *16*, 3575. https://doi.org/10.3390/su16093575

Academic Editors: Rhuanito S. Ferrarezi, Davie M. Kadyampakeni and Ripendra Awal

Received: 13 March 2024
Revised: 12 April 2024
Accepted: 21 April 2024
Published: 24 April 2024

1. Introduction

Water is a vital component in agricultural production, playing a significant role in plant growth. To achieve better agricultural production levels, it is crucial to provide essential and sufficient water at the right time [1]. However, in some regions, traditional irrigation methods are used, with farmers relying on their experience to determine irrigation time and water consumption. This approach fails to meet crop irrigation standards, leading to significant water and manpower waste [2]. One of the key technologies to enable precision agriculture is water management in irrigation systems. Unsuitable irrigation can lead to a decrease in crop yields, emphasizing the need for efficient irrigation in agricultural irrigation management. To provide accurate information about irrigation needs in real time, modern communication technologies such as the IoT and big data can be leveraged [3].

The Internet of Agricultural Things is a network that links agricultural information-sensing devices to the Internet, connecting agricultural production factors and the environment. Through the exchange and communication of information, it intelligently identifies, monitors, tracks, and manages agricultural processes and objects. Combining the IoT with traditional agricultural production methods shifts agriculture from a human-centered production model that relies on isolated machinery to a software-centric production model. This approach requires a large number of automated, intelligent, and remote production equipment. The improvement of agricultural IoT technology in the new era can reduce the cost of agricultural production and increase agricultural profitability. By utilizing IoT technology, various agricultural parameters such as soil moisture, weather conditions, and crop status can be monitored. These parameters can help farmers make timely decisions. For example, based on parameters such as soil moisture and rainfall, the water requirements of crops can be determined, and irrigation plans can be adjusted accordingly. Similarly, soil pH can be adjusted based on soil conditions to provide a suitable soil environment for different crops [4]. Fertilizer types and quantities can be determined based on measurements of soil nutrient levels at specific locations. This can improve fertilizer efficiency and reduce environmental side effects [5]. Accurate pesticide application plans can be formulated based on crop growth status, pest and disease risks, and other factors. This can reduce the improper use of pesticides and mitigate environmental pollution risks [6,7]. The above examples illustrate that the use of IoT not only enables timely action based on accurate information but also facilitates the management and on-demand utilization of agricultural resources such as water, fertilizers, and pesticides. This achieves cost savings and improves production outcomes. With the use of IoT technology, farmers can predict crop yields and market demand [8]. Planned and targeted agricultural production can be carried out based on market demand, thereby reducing economic losses and improving cost-effectiveness. In agriculture, the use of IoT devices such as automated machinery can automate labor-intensive tasks, reducing the need for manual labor and lowering labor costs. The reduction in manual labor and improvement in automation levels will enhance productivity in every aspect of the agricultural sector [9].

The general trend of the Internet of Things in agriculture is to use artificial intelligence technology and IoT wireless communication technology to create a smart agricultural irrigation technology system [8] Wireless communication technology can play a very important role in agricultural irrigation management, which is mainly used in central control systems, field-monitoring systems, control terminals, and pressure-sensing systems. The combination of wireless communication technology and artificial intelligence (AI) can provide intelligent decision support for irrigation systems. Data such as soil moisture and weather conditions collected by sensors are transmitted to the central control system through wireless communication technology. The system utilizes AI algorithms, machine learning, and data models [10–12] based on historical and real-time monitoring data to provide farmers with irrigation decision recommendations and optimization plans. This enables farmers to make scientifically sound irrigation decisions. The integration of wireless communication technology and AI allows for the remote monitoring and management [13] of irrigation systems, along with system warnings. The environmental data and real-time status of irrigation equipment are transmitted to user terminals through wireless communication technology, allowing users to remotely monitor the operational status of irrigation equipment through mobile phones, tablets, and other devices [14]. With AI algorithms, the system can automatically detect anomalies and faults in irrigation equipment and promptly notify farmers to take repair measures, thereby improving the efficiency of irrigation system operation. It can also provide early warnings for disasters, pests, and diseases, and initiate emergency measures, thereby reducing crop losses and economic losses [15]. Most importantly, compared to traditional manual irrigation, this approach helps achieve water-saving goals in agricultural irrigation systems [16]. IoT sensing devices enable the real-time monitoring of soil moisture, weather conditions, and other parameters. The data are sent to the central control system through wireless communication technology, where AI algorithms process and perform predictive analysis on the data. This assists farmers in making scientifically sound irrigation decisions and adjusting irrigation plans in a timely manner, enabling precise on-demand irrigation and reducing excessive and unnecessary irrigation. This greatly minimizes water wastage [17], which is of great significance in water-scarce areas. Climate change can lead to drought or insufficient water supply in regions with water scarcity [18], resulting in environmental issues such as soil salinization and groundwater depletion [19]. By employing IoT and AI technologies in irrigation systems, it is possible to provide crops with adequate water under limited water resources, enhancing drought resistance and ensuring the stability and sustainability of agricultural production. Additionally, it promotes water resource conservation, improves the sustainable utilization of water resources, and protects the ecological environment.

This paper summarizes the existing research on various commonly used wireless communication technologies in the transmission layer of IoT networks. It also explores the application of these wireless communication technologies in agricultural irrigation management, analyzing their merits, limitations, and applicable scenarios. Furthermore, the challenges that arise when using IoT wireless communication technology in agricultural irrigation management are identified and discussed for future consideration.

2. Agricultural IoT Architecture and Wireless Communication Technologies

Most people divide IoT architecture into three layers: the perception layer, the transport layer, and the application layer [16]. This division not only cannot accurately characterize the characteristics and differences of IoT technology in specific industrial applications but also does not reflect the characteristics and differences of specific users. In order to overcome these two shortcomings, some people divide the agricultural IoT system architecture into five layers. That is, the user layer, application layer, transport layer, perception layer, and object layer [20,21]. The functions, components, and relationships of each layer are shown in Figure 1.

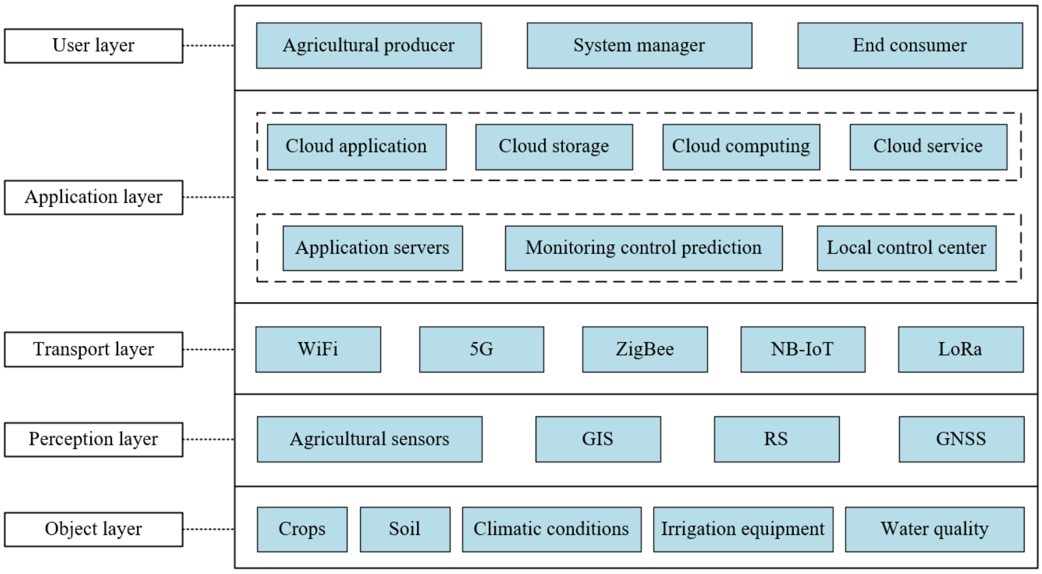

Figure 1. Agricultural IoT architecture diagram.

The user layer is the top layer of the agricultural IoT, primarily targeting users who utilize the agricultural IoT. The user layer can provide a visual interface for users to access agricultural decisions, data reports, and more. The development of the user layer requires improving the accuracy and efficiency of data analysis. Efficient algorithms need to be developed, and emphasis should be placed on integrating data from multiple sources [22] to assist users in making more accurate irrigation decisions. The application layer is responsible for application development and management in the agricultural IoT and interacts with the user layer. The development of the application layer requires improving the reliability of control and execution technologies. This helps reduce device energy consumption and extend the network lifespan [23,24]. It enables precise control and flexible adjustment and enhances the automation and efficiency of the system. The transport layer is primarily responsible for data communication. The development of the transport layer requires improving the reliability and efficiency of data transmission through advancements in communication technology. Suitable communication protocols can be selected to achieve system goals such as, for example, considering the use of LPWAN protocols to achieve long-range and low-power objectives [25]. Optimizing the network topology of the IoT can also improve data transmission efficiency. The proper planning and deployment of transmission nodes can expand communication coverage and improve communication quality [26]. The use of distributed networks or multi-hop networks can enhance network robustness. Data compression and encryption techniques can be improved to reduce data transmission latency and ensure data security and privacy [27,28]. The perception layer is primarily responsible for sensing and monitoring various soil parameters, weather conditions, and other agricultural environmental factors. It manages devices such as soil temperature and humidity sensors, light sensors, weather sensors, soil conductivity sensors, and plant growth detection sensors, which are crucial in agricultural irrigation systems. However, improvements are needed in the accuracy, size, power consumption, and adaptability of agricultural sensors. Additionally, multifunctional sensors need to be developed to monitor more parameters with fewer devices, thereby reducing deployment costs. The object layer involves physical devices, sensors, and actuators. Devices in the object layer typically require battery power, so it is necessary to improve energy efficiency [29,30] and extend the device lifespan. Security measures need to be enhanced to prevent data leakage and network attacks. Additionally, real-time processing, edge computing [31], and adaptive capabilities need to be improved to meet the demands of complex scenarios.

One of the crucial technologies for the transmission layer of IoT networks is to ensure the real-time and dynamic acquisition of agricultural site information. When implementing intelligent agricultural irrigation management, the key to the system's successful operation lies in the agricultural IoT communication technology employed. The data transmission methods of agricultural IoT are primarily divided into two categories: wired communication and wireless communication. Wired communication methods, such as power carriers, optical fiber communication, fieldbus technology, and program-controlled switching technology, have been traditionally used. However, the agricultural production environment is typically considered to be in the wild, and wired data transmission technology is gradually being replaced by wireless communication due to its shortcomings, including high labor maintenance cost, complex wiring, small scale, and proximity. Today, wireless sensor networks (WSNs) have become a research hotspot [32].

Currently, the most widely used information transmission technology of the IoT is wireless communication technology. This technology enables the digital transcoding and transmission of text, pictures, audio, and even video information. Utilizing wireless communication technology improves the transmission speed of various forms of information, which can avoid the issues of information damage and distortion caused by the simultaneous transmission of a large amount of information. As researchers delve deeper into wireless communication technology and apply it to agricultural irrigation management, the use of wireless communication technology in agricultural irrigation is in line with the development goal of agricultural water conservation. Wireless communication technology includes short-range data transmission technology and low-power wide area communication network (LPWA) technology. Short-range data transmission technologies include ZigBee, WiFi, 5G, etc., while low-power wide area networks are a low-power and long-distance communication technology for the IoT, mainly including LoRa (Long-range), NB-IoT (Narrowband IoT) [33], and others. Data rates, coverage, energy consumption, and cost are significant factors to consider when deciding which technology to use. The wireless communication technologies commonly used in agricultural irrigation systems are analyzed and compared in Table 1.

Table 1. Main features of wireless communication technology in agricultural irrigation management.

Parameters	International Standards [34,35]	Operating Frequency [34,35]	Transfer Speed/ (kb·s^{-1}) [34,35]	Communication Distance (Diameter)/km [34,35]	Security [36]	Power Consumption/mA [34]	Cost/USD [34]	Battery Lifetime [36]	Modulation	Channel Bandwidth	Latency	Topology
WiFi	IEEE 802.11a IEEE 802.11b IEEE 802.11g IEEE 802.11n	Sub-GHz 2.4 GHz	1.1×10^4–5.5×10^4	0.02–0.3	Low	Medium	15–25	Several hours	BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM	1/2/4/8/16/ 22 MHz	50 ms	Star, mesh, single-hop, point-to-hub
Fifth-generation	eMBB	30–300 GHz	$<1\times10^7$	0.1–0.3	High	Medium	30–60	Several days	BPSK, QPSK, QAM	40/80 KHz,	1 ms	Star
ZigBee	IEEE 802.15.4	2.4 GHz 868 MHz	10–300	0.02–0.35	Medium	Low	8–15	2 years	BPSK, OQPSK	2 MHz	20 ms–30 ms	Multi-hop, P2P, tree, star, mesh
NB-IoT	3GPP	Cellular Bands Licensed LTE 150 MHz–3.5 GHz	<100	1–10	Low	Low	10–20	7–8 years	QPSK, OFDMA, SC-FDMA	180/200 KHz	1–30 s	Star, cellular network
LoRa	LoRaWAN R1.0	0.5–50 GHz	0.3–50	2–20	High	Low	8–10	8–10 years	CSS, GFSK	25/250/ 500 KHz	3–10 s	Star-on-star, star

As mentioned earlier, wireless communication technologies are commonly used in agricultural irrigation management to facilitate the communication of irrigation systems. Different wireless communication technologies have distinct characteristics, and their suitability depends on the agricultural irrigation scenario. Table 2 provides some examples of the use of wireless communication technologies in agricultural irrigation management.

Table 2. The use of wireless communication technologies in agricultural irrigation management.

Communication Technology	Crop Name/Type	Sensor Measurement Parameters	Index	References
LoRa	grape	Soil moisture, park temperature, wind speed, wind direction	Increased irrigation rates and saved water	[37]
	lawn	Temperature, soil moisture, water flow rate	Water conservation	[38]
		Soil moisture	Reduced system energy consumption	[39]
		Soil moisture, temperature, conductivity	Increased automation	[40]
	garden	Air temperature, air humidity, soil moisture	Saved water and reduced costs	[41]
		Temperature and humidity, soil moisture, light intensity	High prediction accuracy, good system stability, long transmission distance, improved water irrigation rate	[42]
NB-IoT		Air temperature, air humidity, air pressure, soil moisture, water level information, latitude and longitude information	Saved water, improved the degree of automation and the level of informatization	[43]
		Soil temperature and humidity, soil pH, illuminance, air temperature and humidity	Saved labor costs, saved water, saved fertilizer, and improved automation	[44]
	grape	Soil moisture, indoor humidity, indoor temperature	Low cost	[45]
		Soil moisture, soil temperature, conductivity	Increased crop yields, improved water efficiency, and reduced resource loss	[46]
	tomato	Soil moisture, soil temperature, flow rate	Improved water and fertilizer utilization, improved system stability and reliability, and increased tomato yield	[47]
Fifth-generation	olive	Soil conditions, climatic conditions	Improved spectrum efficiency and secrecy	[48]
	tomato	Flow rate	Increased crop yields and achieved water-saving irrigation targets	[49]
WiFi	vegetable	Temperature, humidity, rainfall, soil temperature and humidity, water temperature, salinity, water level	Sensor network coverage	[50]
		Soil temperature and humidity	Improved water and electricity utilization	[51]
		Soil temperature and humidity, soil pH	High efficiency, low cost, high automation	[52]
ZigBee	garden	Garden temperature, soil moisture, rainfall	Low cost, compactness, high performance	[53]
	red oak leaves, red lettuce, Chinese cabbage	Ambient temperature, soil moisture, solar radiation	Saved time and effort	[54]
		Turbidity, temperature, dissolved oxygen, pH	Real-time monitoring of the quality of irrigation water	[55]
		The moisture content of the soil, the temperature and humidity of the air	Low power consumption, high system robustness	[56]
		Ambient temperature, soil moisture, air humidity	Improved unmanned and efficient use of energy	[57]
LoRa/NB-IoT		Soil temperature, soil water content, soil trace elements, air humidity, air temperature, carbon dioxide concentration, illuminance	Easy to operate, low cost, easy to maintain	[58]
LoRa/WiFi	garden	Air temperature, air humidity, soil pH	Reduced water consumption, increased wastewater and stormwater reuse	[59]
LoRa/NB-IoT	grape	Soil temperature, soil pH	Low cost, low power consumption	[60]

3. Literature Review and Motivation

This section provides a review of the research on the use of five wireless communication technologies, namely WiFi, Fifth-generation, ZigBee, NB-IoT, and LoRa. It summarizes the advantages and disadvantages of each wireless communication technology in agricultural irrigation management. The section also reviews the research on the use of multiple wireless communication technologies and summarizes their respective strengths and weaknesses.

3.1. WiFi

WiFi is a wireless LAN technology created by the IEEE 802.11 protocol [61]. As the Internet has developed, WiFi has become widely used in various fields. WiFi boasts many advantages, including wide coverage, high popularity, low cost of use and maintenance, simple networking, and direct access to the Internet.

Lloret et al. [50] developed a WiFi-based sensor network to control flood irrigation in agriculture. The system involves the deployment of wireless nodes equipped with sensors that monitor various parameters in the field. These nodes connect to WiFi-based gateways, creating local networks that allow farmers without technical expertise to view parameters and irrigation status detected by the sensors. They can manage irrigation equipment through their smartphones. Gulati et al. [62] designed a smart irrigation system that employs the IoT, connecting irrigation equipment such as motor pumps with WiFi modules. Every time the motor pump supplies water to the soil, the ESP8266 WiFi module sends a notification to the user application to inform them of the irrigation status. Thakare and Bhagat [52] designed an Arduino-based controlled irrigation system using a WiFi module. It uses temperature, pH, and moisture sensors to detect the moisture content of the soil. When the humidity level falls below the threshold, the humidity sensor signals the Arduino board through the WiFi module, which sends a notification via the IoT platform. Farmers can remotely monitor their farms using the IoT. Rout et al. [51] designed a solar-powered smart irrigation system that can be controlled and monitored remotely through the IoT. The ESP8266 WiFi chip is the main controller unit, and the master controller handles the decision-making and soil moisture content monitoring. The system sends notifications to the user via WiFi, and they can control the irrigation system from anywhere. Pornillos et al. [63] developed an intelligent irrigation control system using a wireless sensor network. The system comprises a sensor module that collects soil moisture data and sends it to a central node through a WiFi connection. The central node analyzes the data and controls the valve's opening and closing to achieve automatic irrigation system control.

WiFi technology is widely used in the automatic monitoring of ecological information, environmental control, and the intelligent management of agriculture. As the most commonly used wireless transmission technology of the current Internet, it works by transmitting signals through a wireless router that accesses broadband, effectively converting wired networks into wireless signals. WiFi boasts high communication rates, strong penetration, fast data transmission, and a large bandwidth. By integrating WiFi technology into intelligent agricultural irrigation management, terminal devices can easily capture images and videos of irrigation areas. Farmers can collect and control irrigation equipment from any location, thanks to WiFi's convenient Internet access. However, the technology is highly dependent on bandwidth, and any signal failures can result in system malfunctions. Moreover, WiFi's data security is poor, making it prone to cracking and data loss during farmland environmental monitoring and data transmission. WiFi is also not suitable for acquiring and storing large amounts of farmland data. Its networking ability is weak, and it can only connect a limited number of devices, usually dozens, making it unsuitable for large-scale farmland irrigation networks.

3.2. Fifth-Generation Communication Technology

Representing the latest generation of mobile communication technology is 5G technology. With its use of a high-band spectrum, 5G mobile networks can achieve incredibly high speeds and low latency. Additionally, their higher bandwidth allows them to connect billions of devices [64], making them an ideal choice for the IoT. This 5G technology effectively breaks the bottleneck of 4G technology, thereby enabling the systematic collection and transmission of massive amounts of information. With its enhanced capabilities, 5G technology can conduct more comprehensive analyses of complex data, including high-dimensional data and high-definition images [65].

Jiang [66] conducted extensive research on the implementation of 5G technology in smart forestry, particularly in the realm of smart irrigation. By utilizing intelligent systems that leverage 5G technology, irrigation equipment can be remotely controlled and managed via a central console. Cloud-based big data can then accurately calculate the precise amount of irrigation water needed based on surface humidity, which in turn maximizes water conservation efforts. Additionally, sensors strategically installed within the forest area continuously monitor for high-temperature hazards and adjust the irrigation time and quantity accordingly. This not only saves water but also ensures that trees are not over-irrigated, thus preventing harm. Massaoudi et al. [48] developed a secure irrigation system that incorporates 5G's essential technologies. Nodes are deployed beneath each tree requiring irrigation and are responsible for sensing various environmental parameters. The collected data are then transmitted to the Remote Service Processor, which compares this information against predefined thresholds. In the event of any deviation from these thresholds, the teleservice processor sends a signal via the 5G network to the brake, which subsequently controls the solenoid valve for irrigation. Xu and Zhang [49] delved into the application of 5G technology within the context of smart agricultural greenhouses, specifically through remote intelligent irrigation instructions and the introduction of a smart greenhouse environmental index control system. By establishing a real-time monitoring and remote control module based on 5G technology, a robust remote communication system is formed, which can enhance the objective assessment value of irrigation water consumption and effectively improve crop growth rates and quality.

This 5G technology has predominantly found its application in unmanned agricultural machinery and crop detection scenarios. Its utilization in intelligent agricultural irrigation management allows for the evaluation of soil moisture, the processing of high-definition audio and video images, and the transmission of data to the cloud for processing and the generation of appropriate irrigation solutions. Moreover, unmanned agricultural machinery can leverage 5G signals to send real-time messages to the control end and swiftly respond to irrigation instructions. This enables on-demand water supply and precise irrigation, thereby enabling intelligent and automated farmland management, effective water quantity management and control, reduced labor costs, and improved resource utilization rates. However, it is crucial to note that 5G technology has certain limitations as well. While 5G wireless communication technology in intelligent agricultural irrigation management can support numerous terminal devices and achieve high integration, 5G cellular technology requires a large number of base stations to be established. This substantially increases the IoT cost of smart irrigation systems and poses challenges in terms of equipment deployment, rendering it unsuitable for large-scale farmland irrigation scenarios.

3.3. ZigBee

ZigBee is a wireless network protocol that features low-speed and short-distance transmission. It adopts the media access layer and physical layer of IEEE 802.15.4 standard [67] specification as its bottom layer. The name "ZigBee" is inspired by the communication method used by bees in bee colonies to transmit food location information to their companions through the "Zigzag" dance [68]. In a ZigBee network, the bees flying freely in the colony manifest as nodes, and collecting honey from different places is equivalent to sensors collecting data. The process of sending honey to the hive for honey brewing is similar to sending collected information to the host computer for data processing [69]. ZigBee is characterized by reliable transmission, short delay, large network capacity, low power consumption, and a low data transmission rate. ZigBee networks are easy to operate and rely on wireless communication methods. Three main network topologies are available, including star topology, tree topology, and mesh topology. Figure 2 shows a schematic diagram of the application of ZigBee technology in agricultural irrigation.

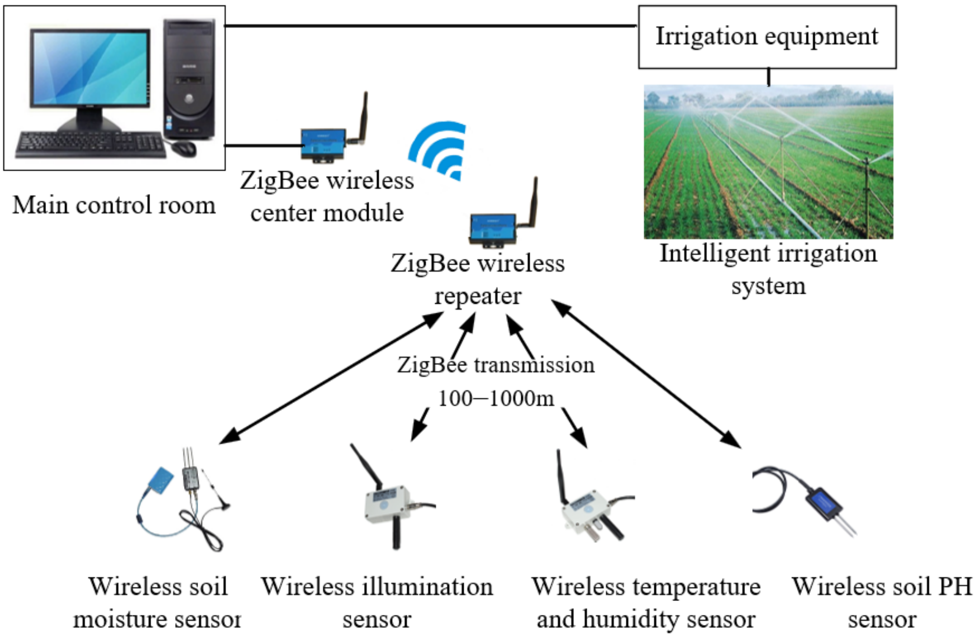

Figure 2. Schematic diagram of the application of ZigBee technology in agricultural irrigation.

Eraliev and Bracco [53] designed an automated irrigation system based on ZigBee. Each end device of the system is equipped with a ZigBee transceiver that reads soil conditions and rainfall, transmitting these data to the coordination station through a ZigBee ad hoc network. The water valve is then controlled based on this information, optimizing irrigation. Sai et al. [54] created a smart irrigation system that uses ZigBee technology, operating via a star topology of the ZigBee communication protocol. The sensor node collects information and wirelessly transmits the data to the host controller via the ZigBee module. The microcontroller is also connected to the ZigBee module for the real-time monitoring of soil conditions and irrigation status. This automatic irrigation system saves significant time and effort. Additionally, Zhang and Kong [55] designed a ZigBee-based farmland irrigation water quality monitoring and control system. The system includes host computer software, a GPRS wireless transmission module, a DSP controller, and a ZigBee network, monitoring water quality in the irrigation area of farmland in real time by utilizing ZigBee wireless sensor networks and DSP low-power processors. The access database was used to develop the background monitoring software for farmland irrigation water quality, enabling back-office personnel to monitor the quality of irrigation water in real time, thereby reducing the crop pollution caused by substandard water. Kirtana et al. [56] developed a smart irrigation system that utilizes ZigBee technology and machine learning. This system comprises two modules: a sensor module and a base station module. The sensor module collects data such as soil moisture, air temperature, and humidity from the irrigation site and transmits them through ZigBee technology to the local base station. The base station module employs machine learning algorithms to train the system to build a classification model and predict crop water demand based on new parameters. By reducing system power consumption, this system offers a more efficient mechanism for irrigating large areas of crops. Chikankar et al. [57] designed an automated irrigation system that employs ZigBee in a wireless sensor network. The sensor node transmits temperature and humidity data to the ADC, which converts the sensory information into digital output. This digital output is then transmitted to ZigBee through UART. ZigBee compares the sensor output to the setpoint and feeds the output to the driver to enable automatic irrigation. Farmers can also customize the crop types in the system. This system solves the problem of high energy consumption in smart irrigation systems.

ZigBee technology is widely used in the intelligent control of agricultural greenhouses, automatic irrigation, and environmental monitoring. By utilizing ZigBee wireless networking, the data collected by the sensor can be transmitted in real time to enable data interaction between the terminal node and the server, thereby allowing for the remote monitoring and control of the irrigation system, which saves significant manpower and material resources. Moreover, ZigBee technology in intelligent agricultural irrigation management can meet the requirements of intelligent irrigation agricultural IoT for low power consumption, low cost, and high security performance. However, ZigBee technology has certain limitations, such as short communication distances, which are generally within 300 m. Currently, intelligent agricultural irrigation management mostly uses ZigBee wireless communication technology, which is only suitable for irrigation scenarios in greenhouses or small, scattered test fields. It cannot be applied well to large farmland in remote areas in the suburbs, nor can it meet the need for low power consumption and long-distance transmission. Additionally, communication stability is weak and susceptible to interference from other signal bands, and ZigBee signals are reflected in a way that is easily affected by obstacles such as buildings and vegetation, resulting in weakened signals and decreased transmission efficiency in complex natural environments.

3.4. NB-IoT

NB-IoT, also known as low-power wide area networks, is a narrowband IoT technology. It is an IoT communication technology that has evolved from 3G/4G cellular communication and operates in dedicated licensed frequency bands. NB-IoT covers a wide range and supports massive connections [70] while offering strong anti-interference ability and high data security as it is organized according to the authorized spectrum. NB-IoT meets many IoT communication needs that cannot be wired and has a wide coverage. The basic architecture of NB-IoT [71] is shown in Figure 3, with three deployment methods available: independent, protection band, and in-band deployment.

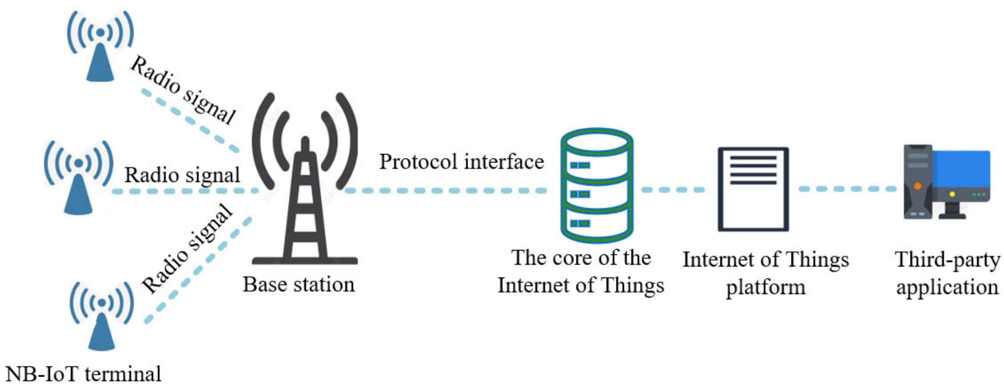

Figure 3. Basic architecture diagram of NB-IoT.

Sun et al. [43] created an NB-IoT-based remote monitoring system for agricultural irrigation canals. The monitoring node collects farmland information, such as air temperature, humidity, and soil moisture, and sends the data at fixed intervals to the remote server via the NB-IoT module. The system resolves the problems of a separate design of water-saving irrigation systems and farmland information collection, improving the automation and informatization levels of canal irrigation monitoring. Liopa-Tsakalidi et al. [45] designed an NB-IoT-based intelligent irrigation platform for vineyards. The system contains IoT nodes that accurately and regularly track soil hydration status. The endpoint is connected to the system backend through NB-IoT, which stores and analyzes the data. Farmers can access their personal dashboards in real time from anywhere with an Internet connection. Zhou and Hu [44] created an intelligent water meter system for agricultural water using NB-IoT. The system uses the pumping station water supply algorithm to indirectly measure water supply, transmitting encapsulated data frames to NB-IoT through RS485. The system uploads pumping station water supply data and status information to the management platform through the IoT cloud platform using NB-IoT technology, facilitating the intelligent management of the water metering system and improving water utilization rates. Li et al. [47] designed an integrated intelligent control system for tomato water and fertilizer based on the IoT. The system employs NB-IOT technology for data transmission, which considers optimal growing conditions and the time of greenhouse tomatoes. This system includes intelligent control and early warning modules, which enhance the accuracy of intelligent irrigation and fertilization for greenhouse tomatoes. Finally, Gao [46] developed a water-saving irrigation system based on NB-IoT. The system arranges solenoid valves and sensors according to the specific needs of the irrigation site, collecting and processing data through NB-IoT terminal nodes. The NB-IoT wireless communication module transmits information to the server through Ethernet, and the server selects the appropriate irrigation scheme based on real-time data. Users can monitor the data on the server in real time or manually adjust control settings. This system enables timely and appropriate irrigation, reducing resource loss.

NB-IoT technology finds its primary use in scenarios such as farmland environmental data collection and agricultural water-saving irrigation. The integration of NB-IoT technology with smart agricultural irrigation management can enhance the development model of smart irrigation in the agricultural IoT. NB-IoT provides a vast coverage area and can accommodate numerous network terminal devices. The technology can transmit data up to a distance of 10 km with low power consumption, making it suitable for large-scale farmland where frequent battery replacements are inconvenient. Even in complex field environments, NB-IoT can ensure stable data transmission, enabling the real-time monitoring of farmland or crops to achieve the goal of precision irrigation. This makes agricultural water-saving irrigation more intelligent, energy-saving, and scientific. However, there are some limitations to the use of NB-IoT technology. The cost of using NB-IoT technology for irrigation communication network networking is high, and in addition to the price of NB-IoT communication modules, operators must also pay operating expenses.

3.5. LoRa

LoRa is an innovative wireless communication technology that offers an ultra-long-distance wireless transmission scheme based on spread spectrum technology, which was adopted and promoted by Semtech in the United States. This technology enables long-range and large-capacity systems while maintaining low power consumption and long battery life, which was previously a challenge for traditional wireless transmission methods. The physical layer of LoRa wireless transmission technology is based on CSS technology, which allows it to better overcome obstacles. Additionally, the codec scheme and spread spectrum modulation technology used make it more resistant to interference and provide better stability against deep fading phenomena, with ultra-high reception sensitivity [72]. Wireless communication using LoRa is an ideal solution for the agricultural IoT, offering low-power, long-range communication technology. LoRa holds great potential for intelligent agricultural irrigation management. A schematic diagram of LoRa technology applied in agricultural irrigation is shown in Figure 4.

Lyu et al. [37] developed a vineyard irrigation control system that utilizes LoRa technology. By combining LoRa wireless communication technology with a dynamic neural network, they created a soil moisture prediction model. The control terminal connects sensors to collect crop growth data and uses LoRa technology to remotely operate pumps, valves, and other equipment. Andrada et al. [38] also created a rural irrigation system using LoRa technology. The system communicates via LoRa and can send trigger signals and calculate water demand to initiate irrigation. Additionally, data are sent to the ThingSpeak cloud through LoRa for monitoring, and the positioning of LoRa devices is determined by optimizing distance and antenna. Mallikarjun et al. [39] designed a farm irrigation control system based on LoRa technology. The system incorporates soil moisture sensors, LoRa transmitters and receivers, MCU modules, and servers. The combination of LoRa technology and MCU modules ensures the secure transmission of soil moisture data from the field to the server, while the data are visualized in various forms.

Farmers without internet experience can remotely analyze the state of their fields with ease. Torre-Neto et al. [40] developed a soil measurement probe that uses a multi-depth sensor and communicates through LoRa technology. The collected data are transmitted to the cloud platform network via LoRa technology, where it can be viewed and analyzed by users. Gloria et al. [41] created a sustainable irrigation system that utilizes the IoT. The hardware nodes responsible for collecting sensor data communicate with each other through LoRa technology and with the server through MQTT, sending data to be stored and analyzed using algorithms. Li et al. [42] developed a water-saving irrigation system for greenhouses that utilizes LoRa and GA-BP. They established a GA-BP crop water demand prediction model and built a demonstration and verification system using LoRa technology networking. The irrigation system collects agricultural environmental factors as input for the prediction model, and the model's irrigation output is fed back to the server via Android APP monitoring software. This enables accurate irrigation and automatic irrigation completion. Vyas et al. [73] designed an efficient fog layer aggregation algorithm for intelligent agriculture that supports LoRa. This algorithm compresses the total amount of IoT data to be uploaded to the cloud, significantly reducing the data volume transmitted to the cloud. It addresses the issue of LoRa communication being unsuitable for transmitting large amounts of data due to its low bandwidth. Ji et al. [74] developed a visualization monitoring solution for agricultural IoT based on LoRa. They reduced the data volume by only sending image patches of modified regions, thereby reducing the utilization of LoRa bandwidth.

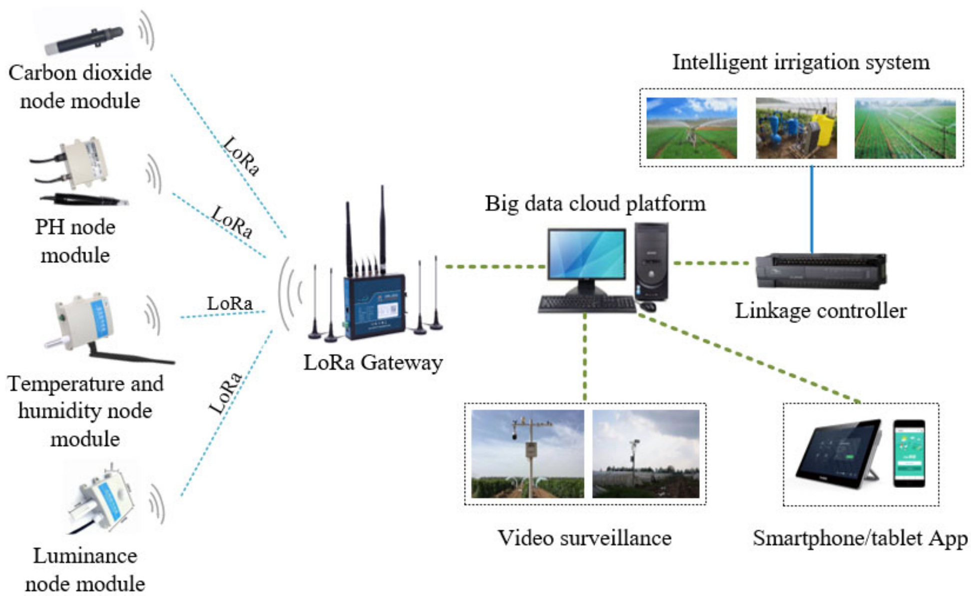

Figure 4. Application of LoRa technology in agricultural irrigation.

LoRa technology is primarily used for data information collection, real-time data analysis, and automatic irrigation. It has the ability to communicate over distances of up to 15 km and is easy to deploy and scale. With a LoRa gateway, tens of thousands of LoRa nodes can be connected, achieving wireless network coverage over a large area. The application of LoRa technology in agricultural irrigation management effectively solves the issues of large irrigation areas, remote geographical locations, and poor mobile signals that are common in agricultural scenarios. LoRa technology enables the real-time collection and remote monitoring of soil moisture and meteorological information in irrigation scenarios. LoRa technology operates within a shorter frequency band and utilizes spread spectrum modulation techniques to enhance system stability and immunity. This leads to increased accuracy and reliability in transmitting data for agricultural irrigation management. By addressing issues related to unstable transmission and low control efficiency, LoRa technology enables automatic and precise irrigation. Additionally, it solves the challenge of balancing long-distance transmission with low power consumption. Through wireless networking, LoRa technology facilitates seamless interconnection without incurring communication fees, significantly lowering the cost of implementing the agricultural IoT in smart irrigation systems. As a result, LoRa wireless communication technology has tremendous potential for revolutionizing agricultural irrigation management.

3.6. Use a Combination of Multiple Communication Technologies

In IoT-based agricultural irrigation management systems, power consumption, transmission range, and application cost are crucial factors to consider when devising intelligent irrigation schemes. Therefore, combining multiple wireless communication technologies in agricultural irrigation management may yield better results. Some articles have documented instances where authors combined multiple wireless communication technologies.

Aldegheishem et al. [59] designed a smart irrigation system that utilizes both LoRa and WiFi communication. The soil monitoring nodes in the system transmit the collected data to the Cluster Head via WiFi. The Cluster Head can use both WiFi and LoRa for transmission and sends information to the Environmental Monitoring Aggregator node. WiFi is used for transmitting data over short distances, while LoRa is used for transmitting data over longer distances. This system effectively reduces the packet loss rate. Li and Yang [58] designed a smart agriculture monitoring platform based on LoRa and NB-IoT technology. Considering the potential high tariffs associated with using all NB-IoT modules, the LoRa terminal node is utilized to collect data and send it to the gateway, which then uses the base station to upload the data to the IoT through NB-IoT technology. The server analyzes and processes the historical and preset parameters using an optimization algorithm and adjusts and corrects the irrigation equipment parameters through the remote node to achieve the optimal state of farmland irrigation parameters. Cardoso et al. [60] designed a sustainable agricultural irrigation approach that utilizes WSN and machine learning. The communication between nodes in the irrigation communication network of the system employs LoRa technology, which enables the use of battery power from sensors, thereby reducing the overall energy consumption of the irrigation system. Communication between nodes and primary servers uses NB-IoT technology, which takes advantage of NB-IoT technology's low power consumption and high performance in data transmission. This system significantly reduces the IoT cost of smart irrigation systems. Goap et al. [75] developed an IoT-based irrigation system that uses machine learning techniques to analyze online weather details and collect soil information and rainfall using sensors. ZigBee technology is used to send the collected data to gateway devices Raspberry Pi and Ariduino Uno. The gateway device then uses the WiFi module to transmit the data to the decision-making platform for further processing. If irrigation is required, the system automatically carries it out, effectively avoiding the waste of water resources during the rainy season.

According to various articles describing LoRa-implemented systems, most authors utilize both wireless communication methods for information transmission. Short-range, low-power, and affordable communication technologies are employed for node-to-node or sensor-to-node communication, whilst long-distance communication is preferred for communication between nodes and remote servers or platforms. Presently, there is a growing interest in 5G and LoRa technologies. LoRa can establish very long communication distances, making it possible for intelligent agricultural irrigation management in remote agricultural environments. LoRa is an excellent solution for irrigation systems that generate less data, and where the data exhibit low system variability. However, for agricultural IoT systems that require transmitting large amounts of data, 5G is the best solution for the limited data transmission capability of LoRa. In the future, combining LoRa and 5G technologies may be considered to better meet the needs of agricultural irrigation management.

4. Conclusions and Prospection

Currently, the agricultural sector has yet to fully embrace intelligent and digital irrigation techniques. Most areas still rely on traditional manual cultivation and irrigation, which demands a significant amount of human resources. Consequently, there is a lack of efficiency and an underutilization of land resources, leading to significant water wastage. However, the application of IoT technology in agriculture has the potential to revolutionize production efficiency and minimize unnecessary manpower expenditure. Farmers can complete real-time monitoring of farmland soil, crop conditions, and meteorological environment, as well as control and manage irrigation equipment remotely, without leaving the comfort of their homes. Additionally, the use of IoT technology enables on-demand irrigation and precision irrigation, thereby reducing water wastage and meeting modern agricultural development standards.

After an extensive literature review, it has become apparent that wireless communication technology has been widely implemented in agricultural irrigation management. The application of wireless communication technology to remotely control irrigation in agricultural irrigation management has become a hot topic in current research. Short-range wireless communication technologies such as 5G, WiFi, and ZigBee offer various benefits. Specifically, 5G has higher bandwidth and lower latency, allowing it to support more smart device connections and transmit large data volumes. WiFi enables high-speed data transmission within a local network but has limited coverage, making it suitable for scenarios with a few connected devices. ZigBee is ideal for small-scale networking but has limited nodes. WAN communication technologies such as NB-IoT and LoRa are also useful. NB-IoT is predominantly used for IoT device connections and has extensive coverage, low power consumption, and a stable connection, resolving the issue of high power consumption in remote farmland information transmission. LoRa combines low power consumption with long-distance communication and is ideal for large-scale sensor networks with broad coverage. Thus, 5G, WiFi, ZigBee, NB-IoT, and LoRa technologies can all be leveraged to manage agricultural irrigation intelligently. However, these technologies differ significantly in terms of performance, each with its advantages and limitations. Moreover, the agricultural IoT is affected by environmental factors such as crop height, topography, field occlusion, farmland size, and meteorological conditions. Therefore, when utilizing wireless communication technology, it is crucial to analyze, optimize, and integrate pertinent technologies to cater to the specific needs of agricultural scenarios.

The advent of agricultural IoT has fueled the integration of IoT technology across various aspects of agricultural irrigation management. However, certain challenges persist in current intelligent agricultural irrigation management, including the following:

(1) Data security issues: Data security and privacy are critical concerns in IoT, and the information communication process in agricultural irrigation management is vulnerable to various security attacks. For example, ZigBee is susceptible to data manipulation and packet decoding, while WiFi is susceptible to interference and passive attacks. Thus, future efforts must focus on enhancing security measures to prevent data breaches, losses, or hackers and provide data security and privacy.

(2) Data fusion issues: As the agricultural IoT technology advances, the volume of agricultural irrigation data is growing exponentially, leading to increasingly complex and diverse irrigation status information. To achieve precise irrigation, significant amounts of state information must be collected, analyzed, and stored. In future work, it is crucial to address the challenge of integrating multiple types of data from various sources, as well as establishing a comprehensive network to enhance the efficiency of data transmission.

(3) Cost issues of agricultural irrigation management systems: Irrigation is not limited to greenhouses or small-scale farmland. In large-scale farmland and complex environments where irrigation network communication is required, equipment usage and maintenance costs must be taken into account. Additionally, more environmental parameters need to be measured at irrigation sites, necessitating the deployment of a

large number of IoT devices. However, high-quality IoT equipment can be expensive, which puts an unnecessary financial burden on farmers. Thus, it is imperative to introduce high-precision, low-cost equipment, and choose affordable communication technology and networking methods to minimize IoT costs.

(4) Multimedia data transmission issue. Due to the low bandwidth of long-range and low-power communication technologies like LoRa and NB-IoT, transmitting image data can result in low efficiency and quality. Images have large data sizes, leading to significant delays and slow transmission speeds. Moreover, data packets of images may get lost or corrupted, causing a partial loss of image information. Traditional image compression algorithms can lead to image distortion, blurriness, or loss of details. Therefore, future research needs to focus on image data compression techniques and transmission optimization strategies specifically tailored for long-distance communication using LoRa and NB-IoT, aiming to improve the efficiency and quality of image transmission.

(5) Electricity and energy issues: Power and energy management are critical aspects of IoT-based deployments in agricultural irrigation applications, where power is a necessary tool and all devices used for communication, monitoring, and storage purposes require energy. Frequent battery replacement is required for certain communication equipment, which indirectly increases costs and is not conducive to energy consumption control in agricultural irrigation systems. Therefore, it is essential to develop advanced methods for strengthening the management of the sensing and communication aspects of IoT to optimize performance and control energy consumption. It is also important to focus on the use of renewable energy to mitigate the energy demand of the deployed system.

(6) System equipment failure: The agricultural irrigation IoT system should be resilient enough to prevent the failure of any single piece of equipment from affecting the overall operation of the system. The deployed irrigation system may face various failures, with hardware equipment failure being the most common. To increase the reusability and customization of system components and services, modular hardware and software components should be considered. The system design should be robust enough to enable the quick detection of system failures and facilitate reconfiguration and self-healing.

The emergence of agricultural IoT is an inevitable development in intelligent and informationized agricultural irrigation management. Although it holds immense potential, there are myriad challenges on the way to its full development. In future research, increased emphasis should be placed on wireless communication technology. The existing intelligent irrigation system should be improved to meet the needs of agricultural irrigation, allowing for the fine adjustment of the irrigation system, on-demand irrigation, and automatic control. Additionally, sensor technology and electronic communication technology should be combined with IoT to ensure comprehensive benefits in agricultural production.

Author Contributions: Conceptualization, P.T.; Methodology, H.L. and Y.P.; Formal Analysis, Q.L. and Y.P.; Resources, Q.L.; Writing—Original Draft, Q.L.; Writing—Review and Editing, P.T.; Visualization, Y.P.; Supervision, H.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Natural Science Foundation of the Jiangsu Province (BK20230549) and the Key Research and Development Program of the Jiangsu Province (BE2021379).

Data Availability Statement: The data are contained within the article.

Acknowledgments: The authors are thankful to the editor and reviewers for their valuable comments in improving the quality of this paper.

Conflicts of Interest: The authors declare no conflicts of interest.

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