Concept of Ecosystem for Smart Agriculture: Millimeter-Wave Information-Centric Wireless Visual Sensor Network

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***Abstract*—The widespread adoption of smart agriculture is crucial not only for food security but also because agriculture is a significant industry outside of urban areas. The common demands for smart-agriculture applications are that real-time video and image data should be effectively collected, shared, distributed, and managed. In our previous studies, we developed an ecosystem that integrated information-centric networking, wireless sensor networks, and millimeter-wave-band (wireless) communications. On the basis of conducting proof-of-concept experiments in a test field for typical smart-agriculture applications, we will develop a new ecosystem that combines the previous platform with visual sensor nodes and artificial intelligence, called a millimeter-wave-band communication information-centric wireless visual sensor network. This paper provides a blueprint for our new research project and identifies technical issues and strategies for their solutions, including implementation, evaluation, deployment, and demonstration on a real farm.**

Keywords—Information-centric networking; wireless visual sensor network; milimeter-wave-band (wireless) communications; ecosystem for smart agriculture

I. Introduction

Agriculture is extremely important in terms of national food security, but the agricultural workforce is aging and decreasing. However, the deployment of information and communication technologies can provide clues to solve these problems. In smart agriculture, there are many application services, such as anti-theft systems for agricultural products, pest-control systems (trapping traps), farm-management robots and tractors (e.g., automatic weeding, cultivating, irrigating, and fertilizing), plastic greenhouse management systems, and disaster-prevention systems. In response to various changes in agricultural circumstances, introducing a smart-agriculture platform can be expected to improve and stabilize productivity. In Japan, there are generally two styles of agricultural businesses: large-scale commercial and small-scale family farms. Large-scale farms aim to supply food for domestic or international markets, whereas small-scale farms protect land in the countryside and act as hubs for the local industry, economy, and community. In our research project, we focus on small-scale family farms.

Through previous studies involving small-scale family farms, we have obtained two opinions regarding barriers to deploying smart agriculture. The farmers have no idea how to use the remote-sensing data effectively, thus they think that smart-agriculture systems incur costs but do not directly contribute to productivity. In other words, as the cost of agricultural materials rises (global inflation), the farmers concentrate on financial and human resources for factors that directly affect agricultural productivity, such as seeds, seedlings, fertilizer, and plastic greenhouses. On the other hand, some young farmers are particularly interested in using smart agriculture to improve their work environment.

TABLE I. COMMON TECHNOLOGIES FOR SMART-AGRICULTURE APPLICATIONS

Applications	*Requirements for common technologies*
Theft prevention	Monitoring from security cameras
Pest control	Monitoring for local circumstances
Field management	Remote control based on real-time video
Greenhouse management	Monitoring of damage and collapse
Weather and disasters	Remote monitoring for field and rivers

For the above background, a common platform should be provided, rather than a different system for each application. Through our research activities and experience, Table I summarizes the requirements of common technologies for smart-agriculture applications, i.e., the platform required to remotely obtain and verify more primitive data, such as real-time videos and field images, different from the sensing data after analysis. In our research project, we propose a new ecosystem that supports an on-demand and real-time video and image forwarding platform based on Information-Centric Networking (ICN), Wireless Visual Sensor Network (WVSN), and Millimeter-wave-band Communications (mmWaves), called mmWave Information-Centric WVSN (mmICWVSN). In this paper, we present the blueprint of the ongoing research and development project as work in progress and provide the details of upcoming study items.

The remainder of this paper is organized as follows. Section II provides related work. Section III discusses wireless networks that can be selected in smart-agriculture applications. Section IV describes the development items needed to complete a new ecosystem as an outcome of this study. Section IV presents the contributions to future wireless technological development. Finally, Section VI summarizes the outcomes and future perspectives of our project.

II. Related Work

There have been many studies and trials regarding smart agriculture, and smart-agricultural equipment is available

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from many vendors [1]. These proposals and solutions are primarily aimed at large-scale farmers, i.e., they are not cost-effective for small-scale farms to deploy. The wireless networks underpinning real-time video and image applications require large capacity and low latency due to the forwarding of streaming data. The proposed scheme uses IEEE 802.11-compliant Wireless Local Area Networks (WLANs) because they can easily integrate the millimeter-wave, microwave, and sub-gigahertz-wave spectrums. There have been many studies on the construction of outdoor WLANs for smart agriculture [2]; however, there are few cases involving millimeter-wave spectrum, e.g., a field trial of mmWaves was conducted in Georgetown, Malaysia [3]. As for the typical ecosystem, the system is implemented on the basis of cloud-native or edge (fog) designs in which the sensing data are centralized in the cloud area (or the partial data are distributed in the edge-node storage). In contrast, the proposed scheme adopts the ICN design in which all data are distributed in the edge-side nodes. The related studies introduced ICN into edge networks, particularly wired networks; nevertheless, the proposed scheme will expand to wireless network areas.

III. WIRELESS NETWORK TECHNOLOGIES SUPPORTING SMART-AGRICULTURE APPLICATIONS

Wireless communication systems for smart agriculture (outdoor environment) are summarized in Table II. The table represents a qualitative comparison among wireless communication systems in terms of each criterion. This is based on the following discussions, and the evaluation was relative to each system, indicating their strengths and weaknesses. The networks being compared are cellular (4G/5G) and satellite networks, Low-Power Wide-Area Networks (LPWANs), Personal Area Networks (PANs) based on IEEE 802.15.4, optical wired networks, and the networks of the proposed scheme. They are compared in terms of communication coverage, network communication (wireless) capacity, and the economic and technical costs of implementation, construction, and deployment.

Cellular and satellite networks are used as de facto standards for wireless communications in outdoor environments. These networks have superior coverage and communication quality, but their operation costs are high. Therefore, small-scale farmers do not approve of them, which is one factor preventing the proliferation of their smart-agriculture applications [4]. Alternatively, LPWANs [5], which can construct a private network with wide-area coverage and low energy consumption, such as LoRa and SigFox, have been widely investigated. However, LPWANs can transfer small amounts of data, such as text-based data or low-resolution (time-lapse) image data; on the other hand, the 100-Hz bandwidth in the 1-GHz band is not sufficient for streaming data transfer. PANs using the 920-MHz band [6], such as ZigBee, 6LoWPAN, Wi-SUN, and Bluetooth, have traditionally been used in wireless-sensor-network research. Considering the coverage of PANs, the deployment is limited to environments inside plastic greenhouses and small-area (campus) networks, even if multi-hop communications are enabled. The wired network is the primary selection in areas

TABLE II. COMPARISON OF WIRELESS NETWORKS FOR SMART AGRICULTURE

Network system	*Coverage*	*Capacity*	*Economic cost*	*Technical cost*
Cellular (4G/5G) satellite networks	**o**	**o**	**x**	**o**
LPWANs (e.g., LoRa)	**o**	**x**	**o**	**x**
PAN (e.g., ZigBee)	**x**	**x**	**o**	**x**
Optical wired network	**x**	**o**	**x**	**o**
Proposed mmICWSN	*	*	*	*

o denotes suitable, **x** denotes not suitable, and * denotes suggested.

where optical fiber lines have already been deployed; however, new optical lines are unrealistic in rural areas for economic reasons.

In contrast, the network structure of the proposed scheme is composed of WLAN based on the IEEE 802.11 standard, in which multiple license-free radio-frequency bands, such as 920 MHz, 2.4, 5, 6, and 60 GHz, are integrated to provide sufficient coverage [7]. Since a gigabit-class data-transmission rate is required for the backhaul network (core network) between agricultural fields and access points, Terragraph (TG) is utilized to achieve the capacity [3]. TG is a 60-GHz-band wireless mesh network platform based on IEEE 802.11 ad/ay that was developed by Meta (Facebook) as an alternative to optical fiber. Regarding cost-effectiveness, since wireless communication devices, modules, and terminals that adhere to IEEE 802.11 are widely used as a well-known Wi-Fi, general-purpose products are easy and inexpensive to obtain. In addition, regarding technical implementation costs, since the proposed scheme can be constructed on the basis of an IP network, the system can provide simple connectivity to various nodes, such as personal computers, tablet computers, and smartphones.

IV. RESEARCH AND DEVELOPMENT ITEMS

In this section, we describe four development items, needed to complete our research project: construction and demonstration of the mmICWVSN, real-time video and image data-transmission scheme, ICN communication-control technology using Artificial Intelligence (AI) based on visual data, and packaging technology and its verification with consideration of horizontal development, as shown in Figure 1.

A. Construction and demonstration of mmICWVSN

In our previous works, we developed a reliable and self-organized ecosystem for co-creative smart cities [8]. Among them, we developed a zero-touch-design node as a sensor node under extreme outdoor conditions. In the previous ecosystem, the inside and outside of the device were connected via water-resistant connectors for waterproof design, and mechanical structures, such as motor drives and cooling fans, were omitted for higher reliability. According to feedback we often receive, the zero-touch-design node device is unsuitable for outdoor environments because it requires a

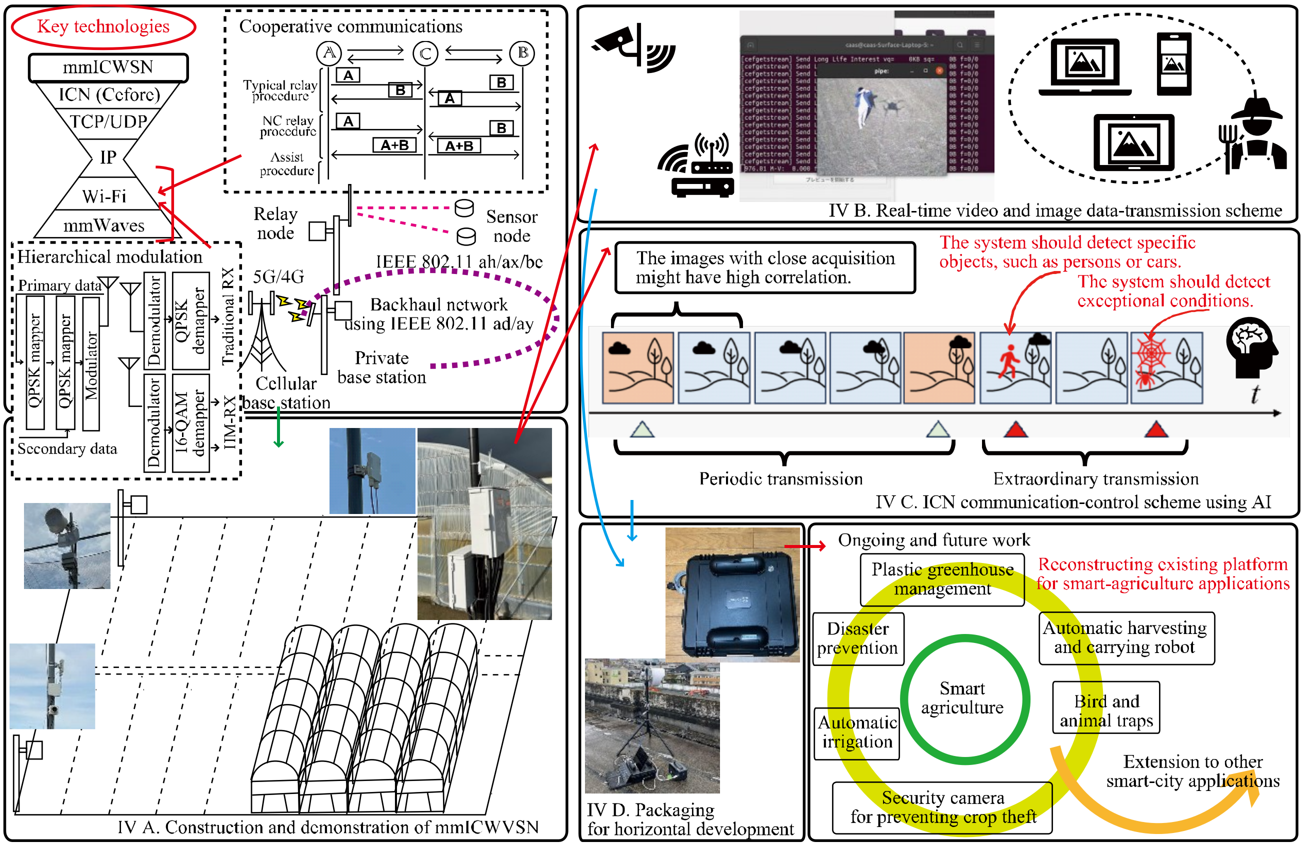

Figure 1. Overview of proposed scheme

commercial power supply. Based on this opinion, there will need to be a commercial power supply in the locations where the system is deployed, i.e., this is not a serious problem.

In the construction and demonstration of the mmICWVSN, we will implement and deploy a system that can be used on actual farms and agricultural worksites. In the TG network, we use a BeMap MLTG-360 as the TG Distributed Node (DN) and MLTG-CN (standard type) and MLTG-CNLR (long-distance type) as the TG Client Node (CN). In our previous network construction research, we constructed test fields [9]. In these test fields, we evaluated and demonstrated the previous ecosystem on the basis of medium- to long-term operational testing. In addition, we evaluated long-distance mmWaves (in Nogata City, Fukuoka, Japan) over a 1-km distance in a line-of-sight environment [10]. Note that the demonstration of the mmWaves is meaningful, as it was carried out in practical environments.

B. *Real-time video and image data-transmission scheme*

This section describes an elemental technology to transmit video and image data using the mmICWVSN. In particular, the proposed scheme is designed as a comprehensive information system that includes farmers, installers, and other relevant persons. In the proposed scheme, we use Cefore [11], an open-source ICN platform that is compatible with CCN/CCNx on a Linux (Ubuntu) environment.

In our previous study [12], we conducted a fundamental experiment, including an evaluation of network performance and real-time video streaming testing between the ground node (TG/DN; MLTG-360) and the aerial node (TG/CN; MLTG-CN) in the test field of a baseball field. Note that the aerial node was implemented using an industrial drone as a mooring node with a 5-m altitude. In the experiment, we transmitted video data in real-time, but the issue was that video broadcasting sometimes froze even when the network conditions were significantly stable. Although we assume that all nodes will be located on the ground in this study, i.e., the issue might not occur, we will continue to investigate the cause of the freeze and improve the quality of streaming-data transmission.

As a part of the personnel-related aspects of the proposed ecosystem, we will develop the system on the basis of feedback gained by interviewing and giving questionnaires to farmers, equipment installers, and government and organization staff. In particular, in the previous implementation, we used Cefore's standard commands via the character user interface, which was not user-friendly for the study participants. To improve accessibility and usability, we will develop the software part of the scheme on the basis of graphical user interfaces, e.g., dashboards and mobile applications. The system will be implemented and its effectiveness evaluated using the mmICWVSN platform.

C. ICN communication-control scheme using AI

The wireless network and its infrastructure require high capacity, low latency, and high reliability for forwarding real-time streaming data. The network structure of the proposed scheme is constructed on the basis of IEEE 802.11-compliant WLANs. The WLANs can support different radio-frequency bands for short-, medium-, and long-distance coverage; nevertheless, bottleneck sections will remain. It is difficult to transmit all video and image data, so we will overcome this barrier using AI-based communication controls.

As a general characteristic of visual data, such as videos and images, the pixels around a particular pixel are often similar, and variations and differences between pixels depend on time and location. Since the visual data generated by smart-agriculture applications does not change significantly over short intervals, the data can be downsampled (compressed). As another approach, the transmission interval can also be adjusted using any event as a trigger. As for executing the trigger, if the correlation value between adjacent images in the time-axis changes significantly or if the AI detects any object, the proposed scheme can be sent as an exception.

Related to this mechanism, in our preliminary study [13], we analyzed the photographic data obtained from an actual farm and then observed a high correlation between the image data adjacent to the time axis. We also found that the correlation value decreased over time. In addition, using YOLO [14], well-known as an object-detection AI, we verified that persons and vehicles could be detected with reasonable accuracy. In detail, we used the official and standard trained model of yolo11x, which is a famous object-detection machine learning platform. However, the accuracy of the general object-detection AI was not sufficient, and there were also many false positives. Therefore, we should improve the accuracy until the system can be used in actual sites. When the system is developed, to reduce implementation costs, we will implement it by combining the Python-based Cefpyco provided by Cefore and Python-based AI.

D. Packaging for horizontal development

As an outcome of our research and development project, the implemented ecosystem, mmICWVSN, will be packaged for horizontal deployment. The packaging here means integrating the ecosystem as a complete platform for practical utilization. The packaged node is a modified version of the zero-touch-design node device, and as a portable device, it combines with the TG, as shown in Figure 2. Thanks to its portability, the device can be placed anywhere outdoors, enabling it to be quickly deployed to meet the diverse demands of smart-agriculture applications. In addition to smart agriculture, the proposed scheme will be applicable to other smart-city applications.

V. CONTRIBUTIONS TO FUTURE WIRELESS TECHNOLOGICAL DEVELOPMENT

This section discusses the proposed scheme's potential to contribute to effectively using the radio spectrum in future wireless communication development. In particular, we focus on technologies for efficient spectrum use and migration to upper (higher) frequency bands.

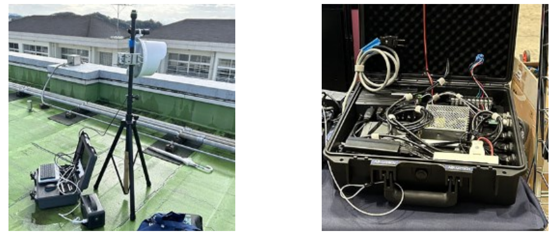

Figure 2. Overview of packaged zero-touch-node device in [11]

A. Contribution in terms of efficient use of spectrum

In the proposed scheme, the elemental technologies that contribute to effectively using the radio spectrum are the ICN scheme and the communication-control technique using AI. ICN can help improve frequency efficiency thanks to its pull-type network design and caching mechanism. Specifically, the ICN-based Internet-of-Things framework sends the data when the user requests it, which can reduce unnecessary data transmission. In addition, with caching techniques, the network node responds with the data stored in its cache memory to requests for the same data, which can reduce duplicate data transmission. On the other hand, controlling AI-based communications enables real-time streaming data to be transferred through the inevitable bottleneck sections in practical wireless networks. To summarize the relevant parts of the preliminary study [15], the data-transmission control and data-compression effects based on the correlation values of the data and the object detection of AI have the potential to contribute to the system's effectiveness. Furthermore, the ICN-based system can also reduce energy consumption as a side effect.

B. Contribution in terms of migration to upper spectrum

In light of the spectrum shortage, shifting to higher frequency bands anytime and anywhere has been investigated. In the proposed scheme, the construction and demonstration of mmWaves will contribute to obtaining meaningful outcomes for future research and development activities. In particular, mmWaves deployment has been trialed in an actual city, Georgetown (Penang, Malaysia) [3]. To the best of our knowledge, there are no other examples. In addition, in our previous studies, according to the evaluation of network performance (e.g., TCP and UDP throughput), the TCP congestion-control mechanism was not suitable for mmWaves. This is because typical congestion controls are suitable for wired networks and current microwave-band WLAN, i.e., it is not considered with the specific characteristics of mmWaves, such as dynamic throughput variation, high packet-error probability, and significant channel conditions due to obstacles such as humans, trees, and leaves. In other words, the characteristics of mmWaves affect the upper-layer protocols. Note that the radio-propagation characteristics of mmWaves have been investigated in other existing studies, but the performances of not only physical-, datalink-,

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network-, and transport-layer protocols but also application-layer protocols have not been clarified.

VI. Conclusion and Future Work

In this paper, we presented a blueprint for developing a new ecosystem for smart agriculture. The main objective of this project is to develop and deploy mmWave Information-Centric WVSN (mmICWVSN) as a new ecosystem for smart-agriculture applications. The proposed scheme integrates ICN, WSN, mmWaves, AI, and related technologies. In future work, we will carry out our plans and expect to achieve our goals. In the network construction regarding the proof of concept of the mmICWVSN, mmWaves (TG) will be needed to ensure sufficient coverage to support the development of the ecosystem. In addition, we will demonstrate the scalability and extensibility of the proposed scheme, and the system is expected to be able to operate stably for medium- to long-term practical operation. In the development of real-time video streaming technology, the application software should be elevated as a comprehensive information system, including in-depth foundational design, software implementation, and embedding on the mmICWVSN platform. Regarding AI-based communication-control technology, the system will need to achieve a detection accuracy (F1 score) of 70%, which is higher than the average accuracy for general AI. Finally, we will package and verify the developed ecosystem for the purpose of horizontal deployment. Specifically, we will investigate two areas: the smart-agriculture field and other smart-city-as-a-service fields. The findings will be able to be provided for related research and development.

Regarding extra future work, the ecosystem developed in this study will also be applied to other areas of smart cities. In addition, it is necessary to consider a broadcast-based wireless communication system as a key technology for edge-side networks by combining ICN and WSN. Based on the strategies identified through the study, the requirements for the key elemental technologies must be provided as feedback in terms of the limitations and potential challenges.

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References

[1] A. U. H. Hashmi et al., "Effects of IoT communication protocols for precision agriculture in outdoor environments," *IEEE Access*, vol. 12, pp. 46410–46421, Mar. 2024.

[2] M. N. Mowla, N. Mowla, A. F. M. S. Shah, K. M. Rabie, and T. Shongwe, "Internet of Things and wireless sensor networks for smart agriculture applications: A survey," *IEEE Access*, vol. 11, pp. 145813–145852, Dec. 2023.

[3] Terragrah, https://terragraph.com/ (retrieved: May 2024).

[4] M. R. Mahmood, M. A. Matin, P. Sarigiannidis, and S. K. Goudos, "A comprehensive review on artificial intelligence/machine learning algorithms for empowering the future IoT toward 6G era," *IEEE Access*, vol. 10, pp. 87535–87562, Aug. 2022.

[5] A. Pagano, D. Croce, I. Tinnirello, and G. Vitale, "A survey on LoRa for smart agriculture: Current trends and future perspectives," I*EEE Internet of Things Journal*, vol. 10, no. 4, pp. 3664–3679, Feb. 2023.

[6] R. Pahuja, H. K. Verma, and M. Uddin, "A wireless sensor network for greenhouse climate control," *IEEE Pervasive Computing*, vol. 12, no. 2, pp. 49–58, Apr.–June 2013.

[7] M. N. Mowla, N. Mowla, A. F. M. S. Shah, K. M. Rabie, and T. Shongwe, "Internet of things and wireless sensor networks for smart agriculture applications: A survey," *IEEE Access*, vol. 11, pp. 145813–145852, Dec. 2023.

[8] K. Kanai, et al., "(Invited) D2EcoSys: Decentralized digital twin ecosystem empower co-creation city-level digital twins," *IEICE Trans. Commun.*, vol. E107-B, no. 1, pp. 50–62, Jan. 2024.

[9] S. Mori, "Test-field development for ICWSNs and preliminary evaluation for mmWave-band wireless communications," *Proc. IEEE CCNC 2024*, Las Vegas, NV, USA, Jan. 2024, pp. 1–2, doi: 10.1109/CCNC51664.2024.10454799.

[10] S. Mori, "Network-performance evaluation for millimeter-wave information-centric wireless-sensor-network ecosystem in actual city," *Proc. IARIA ICN 2025*, pp. 7–11, Nice France, May 2025.

[11] Cefore, https://github.com/cefore/cefore/ (retrieved: May 2024).

[12] S. Mori, "MmWave UAV-assisted information-centric wireless sensor network for disaster-resilient smart cities: Preliminary evaluation and demonstration," *Proc. IARIA ICN 2024*, pp. 1–4, Barcelona, Spain, May 2024.

[13] S. Mori, "A study on information-centric wireless visual sensor network for smart agriculture applications," *Proc. RISP NCSP 2025*, pp. 485–488, Pulau Pinang, Malaysia, Feb.–Mar. 2025.

[14] YOLO, https://ultralytics.com/ (retrieved: May 2025).

[15] S. Mori, "Development of UAV-aided information-centric wireless sensor network platform in mmWaves for smart-city deployment," *International Journal on Advances in Networks and Services*, vol. 17, no. 3&4, pp. 105–115, Dec. 2024.

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