Information-Centric Wireless Sensor Network Framework for Smart Agriculture: Concept Proposal, System Design, and Preliminary Evaluation

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***Abstract*—Widespread adoption of smart agriculture is crucial not only for food security but also because agriculture is a significant industry outside of urban areas. Smart-agriculture applications must collect, share, distribute, and manage video and image data in real time. Our previous studies developed a network that integrated information-centric networking, wireless sensor networks, and millimeter-wave-band (wireless) communications. We recently conducted proof-of-concept experiments in a test field for typical smart-agriculture applications on a new platform 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 describes the platform, the system design required to implement it, and simulation results on the wireless network characteristics of the system in the target environment. In addition, this paper identifies technical issues regarding implementation, evaluation, deployment, and demonstration on real farms and strategies for their solution.**

Keywords—Information-centric networking; millimeter-wave-band wireless communications (mmWaves); platform deployment for smart agriculture; wireless sensor networks

I. INTRODUCTION

Internet connectivity is accelerating as new online social networking, live streaming, video sharing, multi-user online gaming, and Internet of Things (IoT) applications emerge. These applications are the elements of smart cities, and the Wireless Sensor Network (WSN) is a critical enabler technology. Internet semantics have shifted from host-centric to content-centric, as can be seen in the emergence of content delivery networks, web caching, and peer-to-peer networking. A paradigm shift is sorely needed toward Information-Centric Networking (ICN), which is a potential network architecture for the next-generation Internet [2]. Furthermore, ICN and WSNs concepts can be integrated to yield Information-Centric Wireless Sensor Networks (ICWSNs) framework.

ICN names individual data rather than addresses. Publisher (sensor) nodes generate sensing data as named data and commit it to the ICN architecture. In the data-retrieval procedure, the subscriber (user) node sends an 'interest message' (a data-acquisition request), and the nearest node replies with the requested (cached) data. If the node does not have the data, the interest message is forwarded to other nodes. To implement this procedure, ICN nodes have three databases: Pending Interest Table (PIT), Forwarding Information Base (FIB), and Content Store (CS). The PIT registers the interest messages, including in- and out-of-interface names enabling requested data to be forwarded to the data requester by back-tracing. If the ICN node has the data, the node replies with its data; otherwise, it relays the interest message. The CS manages cached data; i.e., nodes can use it to check whether the requested data is available. During data forwarding, intermediate nodes along the routing path copy and store the data in their cache memories.

Thanks to its in-network caching mechanism, ICN can provide efficient data sharing without relying on its location; as a result, network traffic can be significantly reduced in an autonomous, decentralized network environment. In general, in-network caching schemes are classified into on-path and off-path methods [3]. Typical ICN platforms support on-path methods. In on-path caching, the intermediate nodes along the routing path perform caching. On the other hand, in the off-path method, nodes outside the route cache the data. Here, the off-path method can be effectively investigated in a multicast network environment; ICWSN is a suitable scenario due to its distributed, decentralized network, and broadcasting and overhearing communications. The use of coding to improve the effectiveness of the off-path caching is under consideration. For example, the most well-known technique, Network Coding (NC), can improve network throughput and scalability in multisource and multicast scenarios. The basis of Superposition Modulation (SM) and Hierarchical Modulation (HM) has been investigated as a way for code-based caching in the physical layer to superimpose signals during modulation [4].

At the same time, these technologies are critical components underpinning the smart-city-as-a-service frameworks. Among these frameworks, agriculture is extremely important for national food security, but the agricultural workforce is aging and shrinking. Here, the deployment of information and communication technologies can help to solve these problems [5]. Smart agriculture has many applications, including 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. Introducing a smart-agriculture platform can improve and stabilize productivity in response to various changes in circumstances. In Japan, there are generally two styles of agricultural business: large-scale commercial and small-scale family farms. Large-scale farms aim to supply food to domestic or international markets, whereas, small-scale farms protect land in the countryside and serve as hubs supporting local industry, the economy, and the community.

Previous studies on small-scale family farms identified two barriers to the deployment of smart agriculture [1]. One is that some farmers often have no idea how to use remote-sensing data effectively; thus, they think that smart agriculture systems are costly and yet do not directly increase productivity. In other words, as the cost of agricultural materials rises (from global inflation), these farmers would rather focus on managing financial and human resources and regard the purchase of seeds, seedlings, fertilizer, and plastic greenhouses as factors that directly affect agricultural productivity. On the other hand, some young farmers are interested in using smart agriculture to improve their work environment. Given these findings, we consider that a common platform should be provided rather than a separate system for each application. Table I summarizes the requirements of common technologies for smart-agriculture applications on the basis of our research and experience. The platform requires sufficient flexibility to support diverse application workflows, including Quality-of-Service (QoS)-required and streaming service workflows for real-time video and field images, that are distinct from the analyzed sensing data.

In this paper, we present the details of study items in our ongoing research and development project [1][6]. In particular, we identify and discuss potential challenges and examine the results of simulations to make preparations for a practical implementation.

This paper presents the following research contributions.

- Considerations based on the findings of previous theoretical studies, the protocol design, and a preliminary evaluation to determine the parameters of the wireless network.
- Expected situations and their solutions, including key technologies for ICWSN and for supporting smart-agriculture and associated applications.
- Identifying specific scenarios regarding the social implementation of ICWSN, including IoT frameworks based on the ICN platform. To the best of the author's knowledge, there are few studies on this aspect.

The remainder of this paper is organized as follows. Section II provides related work. Section III describes the development items needed to complete a new ecosystem as an outcome of the (future) research project and ongoing work. Section IV presents the research contributions to future wireless technological development. Section V describes the protocol design. Section VI presents the numerical results of a preliminary evaluation. Finally, Section VII summarizes the outcomes and future perspectives of our project.

II. Related Work

Bilal et al. [7] proposed a solvable linear network-coding scheme for the ICN architecture, and Llorca et al. [8] formulated the ICN-based multicasting model and analyzed its use. using it. Ramakrishnan et al. [9] adopted an NC-based ICN scheme to video streaming and Yang et al. [10] used it as an energy-saving technology in WSNs. Yin et al. [11] investigated the issue of cooperative communications where two adjacent nodes mutually recover lost packets in a lossy wireless broadcast channel. You et al. [12] examined joint use of the NC and HM techniques to provide asymmetric data rates. In particular, Tang et al. [13] presented combined HM and physical-layer NC techniques for downlink asymmetric two-way relay channels. Tharranetharan et al. [14] proposed to combine the HM and NC techniques by using a bit-interleaved coded modulation method to improve the bit-error probability.

TABLE I. COMMON TECHNOLOGIES FOR SMART-AGRICULTURE APPLICATIONS

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

There have been many studies on smart agriculture, and smart-agricultural equipment is available from many vendors [15]. Their 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 (mmWave), microwave, and sub-gigahertz-wave spectrums. There have been many studies on the construction of outdoor WLANs for smart agriculture [16]; however, there are only a few studies involving the mmWave spectrum; e.g., a field trial of mmWaves was conducted in Georgetown, Malaysia [17]. The ecosystem is typically implemented on the basis of cloud-native or edge (fog) designs in which the sensing data are centralized in the cloud area (or the data are distributed in the edge-node storage). In contrast, the proposed scheme adopts the ICN design in which all data are distributed among the edge-side nodes. The related studies introduced ICN to edge networks, particularly wired networks; the proposed scheme expands the scope to wireless network.

III. Research and Development Items for Smart-City Deployment for Smart Agriculture

This section presents the research and development challenges of deploying a smart-agriculture platform based on the proposed elemental technologies.

A. Key technology: Cooperative communications scheme based on coded off-path caching method

Figure 1 provides an overview of the proposed scheme, including the research and development items. Our previous studies preliminarily investigated a novel NC-based

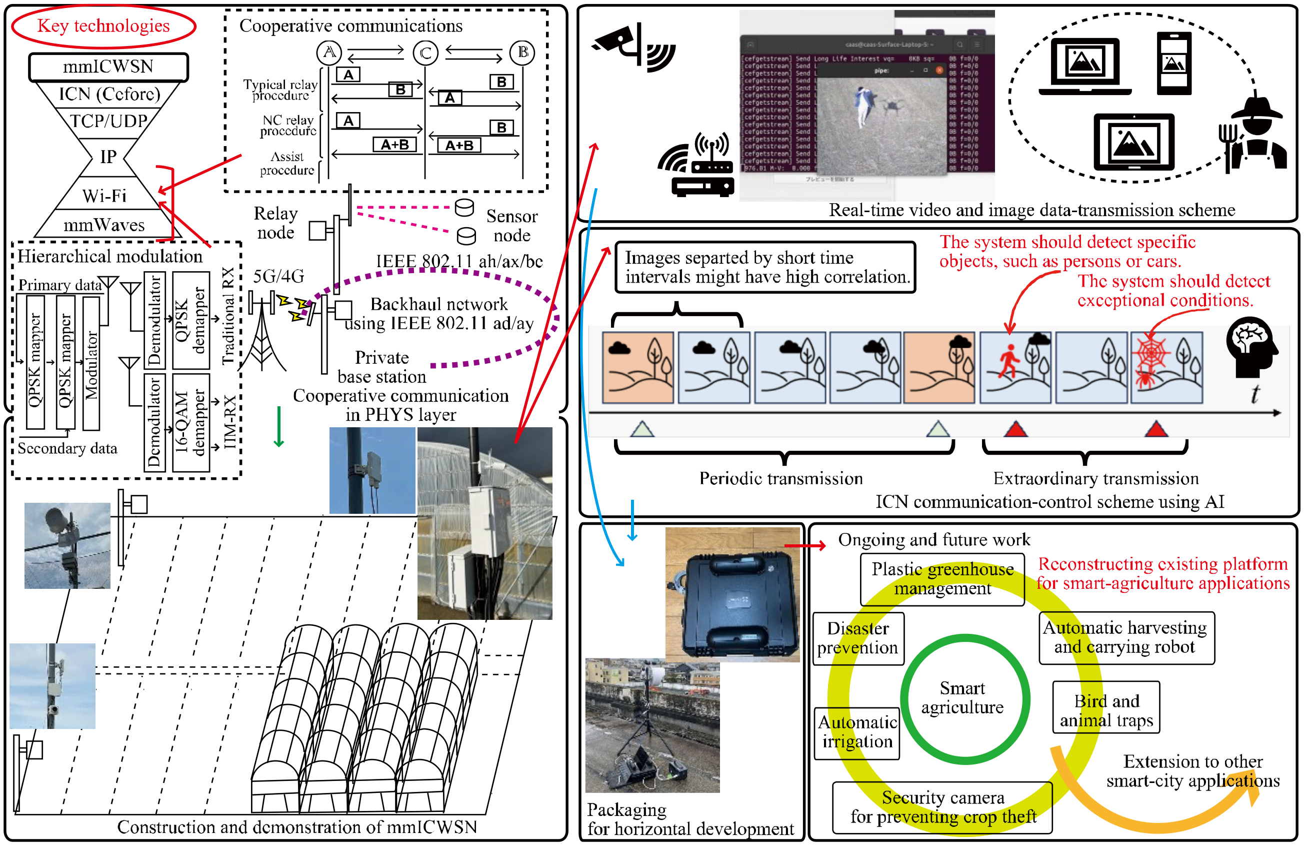


Figure 1. Overview of research and development items for smart-city (smart-agriculture) applications

cooperative communication scheme with constructive interference [4]; this scheme used the HM technique to reduce overhead, i.e., eliminate one of the data transmissions, during the cooperative phase. The transmitter-side node encodes two data bits using the Exclusive OR (XOR) operation bit-by-bit. In contrast, the receiver-side node decodes all the received data once. In this way, NC offers both distributed data storage and efficient multipath solutions to ICN. HM divides the data into two or more streams with different degrees of protection. All receivers can retrieve the most important data bits (primary data stream). The less important data bits (secondary data stream) can be received by some receivers that can decode the HM-based superposition data or by receivers in better reception conditions, such as those near the transmitter. For example, the combination of 4 and 16-Quadrature Amplitude Modulation (QAM) provides a two-level hierarchy. In this modulation scheme, the primary and secondary data streams are assigned to upper and lower bits, respectively, at the bit-to-symbol mapper. All receivers can demodulate (detect) the primary data in the received signal by using the symbol-to-bit demapper in 4-QAM (i.e., QPSK; Quadrature Phase-Shift Keying), while HM-available receivers can demodulate both primary and secondary data by using 16-QAM.

B. Development and deployment of the ICWSN platform

In our previous studies, we developed a reliable and self-organized testbed for co-creative smart cities [18]. The testbed is equipped with a zero-touch device designed for extreme outdoor conditions. Namely, the inside and outside of the device are connected via water-resistant connectors for a waterproof design, and mechanical components, such as motor drives and cooling fans, are omitted for greater reliability. According to feedback we often receive from farmers testing the equipment, the device remains unsuitable for outdoor environments because it requires a commercial power supply. Accordingly, a commercial power supply will be needed at the locations where the system is deployed; i.e., this issue is not considered critical.

The testbed will be deployed on an actual farm as a demonstration of the ICWSN platform. So far, the efficiency and fault-tolerance characteristics have been evaluated through computer simulations [19][20]. This paper focuses on the feasibility of achieving such advantages by presenting a protocol design prior to a real-world evaluation. The network of the ICWSN platform is composed of WLANs 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. The mmWave of our platform use Terragraph for the backhaul network (core network) between agricultural fields and access points. Terragraph was developed by Meta (Facebook) as a wireless alternative to optical fiber and can be used to construct a 60-GHz-band wireless mesh network platform based on IEEE 802.11 ad/ay [17]. In our platform, a BeMap MLTG-360 will be used as the Distributed Node (DN), and MLTG-CN (standard type) and MLTG-CNLR (long-distance type) will be used as the Client Node (CN) [21]. Our previous network-construction experiment, which involved a field test on the testbed, demonstrated medium- to long-term operations. In addition, an experiment on long-distance mmWaves was conducted over a 1-km distance in a line-of-sight environment (in Nogata City Fukuoka, Japan) [22].

C. Real-time visual data-transmission scheme

This section describes the key technology for transmitting real-time visual data, such as video and images, via the ICWSN platform. The proposed data-transmission scheme is designed as a comprehensive information system that includes farmers, installers, and other relevant people. Our previous study [23] conducted a field test that included an evaluation of network performance and real-time video streaming testing between the ground node (MLTG-360) and the aerial node (MLTG-CN). The aerial node was a mooring node at a 5-m altitude, and it was implemented using an industrial drone. Cefore [24] was used on the test devices as an open-source ICN platform compatible with CCN/CCNx in a Linux (Ubuntu) environment. Using Cefore's standard commands, video data can be transmitted in real time. However, it was found that the video sometimes froze even when network conditions were stable. This issue will be tackled in the future, but the nodes will initially be placed on the ground.

Furthermore, the ICWSN platform will be developed to account for human-centered aspects pointed out in interviews and questionnaires with farmers, equipment installers, and government and organization staff. In particular, the previous implementation used Cefore's standard commands via the Character-User-Interface (CUI)-based terminal, but study's participants indicated that it was not user-friendly. To improve accessibility and usability, the ICWSN node's dashboard should instead be visualized based on Graphical User Interface (GUI), such as personal-computer, tablet-terminal or mobile-phone applications. Eventually, the above mentioned ICWSN solutions should be implemented and its effectiveness evaluated using the ICWSN platform in the on-site farms.

D. Wireless communication control based on AI for ICN

The wireless network and its infrastructure require high capacity, low latency, and high reliability. Its architecture is thus based on IEEE 802.11-compliant WLANs. WLANs can support different radio-frequency bands for short-, medium-, and long-distance coverage; however, bottlenecks remain. It is difficult to transmit all the visual data collected by the platform, so we will try to overcome this issue by using Artificial Intelligence (AI)-based ICN controls. A general characteristic of visual data is that nearby pixels are often similar, and their color and intensity variations depend on the 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). Moreover, the transmission interval can also be adjusted using an event as a trigger. When executing the trigger, if the correlation value between adjacent images along the time axis changes significantly or the AI detects an object, the AI-based node devices can be sent as an exception.

Our preliminary study [6] analyzed photographic data from an actual farm and found a strong correlation between image data nearby on the time axis. We also found that the correlation value decreased over time. In addition, by using YOLO [25], a well-known object-detection AI, we verified that persons and vehicles could be detected with reasonable accuracy. Here, we used the standard trained YOLOv11x model. However, it was not sufficiently accurate and detected many false positives. To reduce implementation costs, we plan to combine the Python-based Cefpyco provided by Cefore and a Python-based AI. AI is used at edge-side nodes to reduce network traffic within the network and to the cloud. Regarding the relationship between the accuracy of AI-detected events and network traffic, higher accuracy does not necessarily lead to a reduction in traffic. If only carefully selected higher-quality data is sent to the network, it will reduce network congestion. A detailed evaluation in the AI environment described in this section will be carried out once the mmWave-band ICWSN platform is deployed to the farm.

E. Packaging and its validation for horizontal scalability and applicability

At the end of this research project, the ICWSN platform will be packaged for horizontal deployment. The packaging involves integrating a suite platform as a smart-agriculture ecosystem for practical use. The packaged platform will be a modified version of a zero-touch-design node device with mmWave support. Thanks to its portability, the device can be placed anywhere outdoors, enabling quick deployment to meet the diverse demands of smart-agriculture applications. In addition, for scalability perspective, the platform can be used in other smart-city applications, such as smart factories (industries) and smart things.

IV. Discussion on Future Deployment to the Field

Here, we will discuss the requirements that must be met by key technologies in the physical (PHY) and Media Access Control (MAC) layers and identify the issues regarding their deployment within smart cities. In particular, we will discuss their potential in future wireless communications from the aspects of efficient spectrum use and migration to upper (higher) frequency bands.

A. Validity of the network structure in proposed scheme

The mmWave-complient ICWSN platform will be implemented, constructed, and deployed on actual farms and agricultural worksites. Here, let us discuss the wireless communication systems supporting those scenarios. Table II is a qualitative comparison of wireless communication systems for smart agriculture (outdoor environment) across different criteria. The individual evaluations indicate strengths and weaknesses relative to the other network types in the table. The compared networks include commercial cellular (4G/5G)

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.

and satellite networks, Low-Power Wide-Area Networks (LPWANs), Personal Area Networks (PANs) based on IEEE 802.15.4, optical (wired) networks, and the network layout of the proposed ICWSN platform. The criteria are 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 offer superior coverage and communication quality, but their operational costs are high, and their coverage flexibility is relatively limited since it is provided from cellular operators, i.e., the users cannot be decided to the coverage area. As such, small-scale farmers tend not to approve of them, which is one factor preventing proliferation of their smart-agriculture applications [26]. LPWANs [27], 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 only transfer small amounts of data, such as text or low-resolution (time-lapse) images; the 100-Hz bandwidth in the 1-GHz band is not sufficient for transferring streaming data. PANs using the 920-MHz band [28], such as ZigBee, 6LoWPAN, Wi-SUN, and Bluetooth, have been used in WSN research. PANs can be deployed only in small environments, such as university campuses and plastic greenhouses, even with multi-hop communications enabled. Wired networks are the primary option in areas where optical fiber lines have already been deployed; however, deploying new fiber lines is unrealistic in rural areas due to economic constraints.

The network architecture of the proposed scheme is based on a WLAN compliant with the IEEE 802.11 standard, integrating multiple license-free radio-frequency bands to provide sufficient coverage. Gigabit-class data transmission rates are required for the backhaul (core) network between agricultural fields and access points, and mmWaves (Terragraph) have this capacity. Regarding cost-effectiveness, wireless communication devices, modules, and terminals that adhere to IEEE 802.11 are inexpensive and readily available. Regarding technical implementation costs, since the proposed scheme can be built on an IP network, the system can provide simple connectivity to various nodes, such as personal computers, tablet computers, and smartphones.

B. *Contribution in terms of efficient use of spectrum*

The key technologies that enable effective use of 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 IoT framework sends data only when the user requests it, thereby reducing data transmissions. In addition, with caching, the network node returns the data from its cache when requested, reducing duplicate data transmissions. On the other hand, AI-controlled communications enable real-time streaming data to be transferred across the inevitable bottlenecks in practical wireless networks. To summarize the relevant parts of the preliminary study, it can be concluded that data-compression effects based on data correlation and AI-based object detection have the potential to enhance the system's effectiveness. Furthermore, the ICN-based system can also reduce energy consumption as a side effect.

C. *Contribution in terms of migration to upper spectrum*

Shifting to higher frequency bands anytime, anywhere has been investigated as a way of dealing with the spectrum shortage. Here, the use of mmWaves could help to achieve meaningful outcomes for future research and development activities. However, although mmWave technology has been deployed in trials in an actual city, Georgetown (Penang, Malaysia) [17], to the best of our knowledge, there are no other examples. In addition, in our previous studies, network performance evaluations (measuring, e.g., TCP and UDP throughput) indicated that the TCP congestion control mechanism was not suitable for mmWave transmissions. This is because typical congestion controls that are suitable for wired networks and current microwave-band WLAN are not designed for the specific characteristics of mmWaves, such as dynamic throughput variation, high packet-error probability, and channel conditions affected by obstacles like humans, trees, and even 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 studies, but the performances physical-, datalink-, network-, and transport-layer protocols well as those of the application-layer protocols have yet to be clarified.

D. *Realistic workload model*

The proposed ICWSN platform targets a smart agriculture scenario using cameras and visual data transmissions. The visual data is from cameras monitoring farms, greenhouses, and the surrounding environment, e.g., irrigation, canals, and weather conditions. It is expected that most of a monitoring session will consist of periodic images with minimal variation that is sent as sequential data. In fact, an analysis of images from an actual greenhouse confirmed this expectation [6]. On the other hand, when the AI in the proposed scheme detects people, vehicles, or wildlife in the framed image, it triggers communications and sends the relevant data. In traditional IP-based WSNs, because of their push-based architecture, data must be continuously sent to the cloud. In contrast, since ICWSN is a pull-type system that retrieves data only when necessary, it is expected to reduce network traffic compared with conventional systems. Note that the ICWSN cannot receive any abnormal events unless the user requests them at a desired time. To tackle this issue, the proposed scheme incorporates an AI-based control.

V. PROTOCOL DESIGN FOR FUTURE DEPLOYMENT

Here, we discuss the feasibility of deploying a PoC-based system in the field. Prior to the experiment, we specify the protocol design and its procedure.

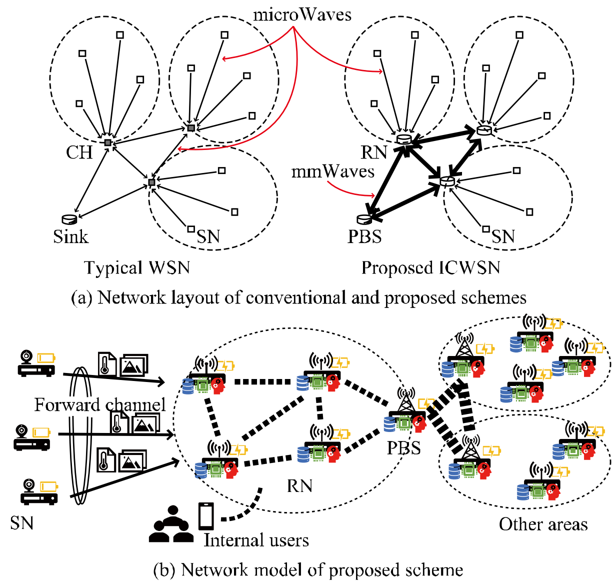
A. Network model

Figure 2(a) compares the proposed scheme's network layout with that of a typical WSN. The WSN is divided into several groups of Sensor Nodes (SNs), and each group selects a Cluster Head (CH) from its members. The CH collects the data from the SNs and sends it to the sink. In the proposed scheme, the network consists of SNs, Relay Nodes (RNs), and a Private Base Station (PBS). Moreover, while WSNs use the microwave wireless communications, the proposed scheme uses both mmWaves and microwaves, and the PBS andRNs work across both air interfaces. As shown in Figure 2(b), the proposed scheme uses RNs, which are higher in performance than SNs, instead of CHs, and a PBS rather than a sink node. The computing performance, reliability, battery capacity, and communication performance of the RNs and the PBS are higher than those of the SNs. The proposed scheme envisions the use of one PBS, several RNs, and dozens of SNs in the observation field.

The SNs acquire the information, e.g., a sensor measurement (text-based data) or an image captured by a camera (visual data). They packetize the data and send it as sensing data to the network. The SNs and RNs are distributed and have a leader-follower relationship via the shared wireless links. The wireless link between each SN and RN has a forward channel (in uplink) for sensing data and a backward channel (in downlink) for control messages. Note that this paper assumes that the SN can access the nearest RN in a single hop. The sensing data are finally forwarded to PBS, which coordinates the RNs in the local area in an edge-side network with a mesh topology. PBS includes the RN functionality and a proxy for external networks. When necessary, it shares a portion of the sensing data with the cloud. Users who request data acquisition are assumed to be located within the internal network; i.e., they access the nearest RN and exchange sensing data and control messages in accordance with the ICWSN procedure described later.

B. Procedure of passing control messages

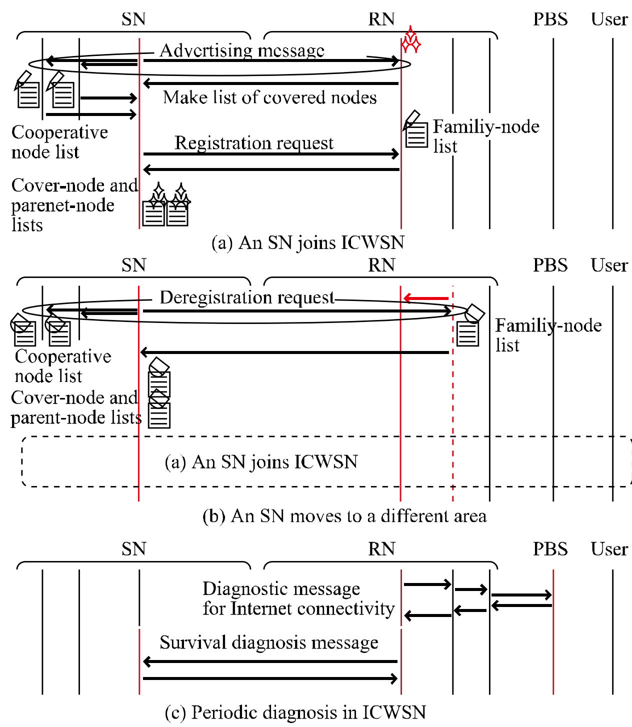
Figure 3 shows the procedure of passing control messages. To shift computational functions, such as analysis and command determination, from the cloud to edge-side nodes, the RN is equipped with a functor that uses queues and a database. As shown in Figure 3(a), when an SN joins the ICWSN, the cover-node list of SNs, RNs, and the PBS located within the coverage area held by the SNs has to be updated. To perform this operation, the new SN advertises (broadcasts) a scan message to neighbor nodes, and then the SNs that received it respond after a backoff time has elapsed to prevent packet collisions. At this time, the responding SNs store this



(a) Network layout of conventional and proposed schemes

(b) Network model of proposed scheme

Figure 2. Network layout and model of the framework



(a) An SN joins ICWSN

(b) An SN moves to a different area

(c) Periodic diagnosis in ICWSN

Figure 3. Procedure of sending control messages in proposed scheme

information in their cooperative node lists, which are used in the cooperative communication mechanism described in Section III.A. Next, the new SN selects the nearest RN as its parent node from the cover node list and sends a unicast registration message for the SN to join the RN's family (member). Upon receiving and accepting the proposal, the RN appends the SN to its family node list and sends a response message. Finally, the SN appends the RN to its parent node list as its parent node. Note that the parent node list and family node list are the databases associated with the FIB in the ICN layer, and the SNs (and RNs) can only have RNs or the PBS as parent nodes.

As shown in Figure 3(b), when an SN moves, it sends a deregistration request to the (parent) RN to remove the registration. The RN then removes its registration from the SNs' cooperative node list. Then, a new connection in the new location is established according to the procedure in Figure 3(a). To ensure ICWSN's availability, it is necessary to periodically confirm the node's survival and verify connectivity to the external network. As shown in Figure 3(c), the RNs periodically verify the connectivity to the PBS, and the survival and connectivity of the SN are guaranteed through periodic one-hop connectivity verification between the SN and the (parent) RN.

C. Procedure of data collection (publishing) and retrieval

Figure 4 shows the procedure for handling the named data. As shown in Figure 4(a), cooperating SNs share part of this data with each other and with the RN. Note that, the AI-based method described in Section III.D filters the data to reduce network traffic. In addition, to use this mechanism, the data can be replied to even if the SN cannot answer; in such case, the RN (or a cooperative SN) responds as a proxy by using the SN as a caching mechanism. Regarding data retrieval, as shown in Figure 4(b), send an interest message (i.e., data retrieval request) to the network, similar to in the typical ICN framework. The interest message includes information about the desired data, such as its time and location. On the basis of the information in the interest message, it is forwarded to the RN, which stores the data to meet the requirements of the request. In accordance with the in-network caching mechanism of ICN, if the PBS (an RN along the previous routing path) has the data in its cache, it can respond to the request. Note that, when placing the RN in the configuration shown in Figure 4(b), the RNs closer to the PBS are more likely to be found before reaching the final RN. In addition, data retrieved at this time can improve the probability of content hits if it is frequently retrieved; therefore, it should be stored in the RN.

When the interest message reaches the final RN, there are different response scenarios depending on the message's time and location. If the time and location conditions are relatively relaxed, the RN will reply with the cached data. In other words, it will reply with the cached data when the time restriction is sufficiently large for data to be acquired and shared in short intervals. In this case, the response data is the caching data periodically shared in Figure 4(a). When time and location constraints are strict, and the user requires the latest data, the RN forwards the interest message using the family node list. The response data is the original data, and the RN caches it using a first-in-first-out algorithm for subsequent interest messages to improve the cache-hit probability. A key feature of ICN is that it does not require data from a specific node, unlike traditional host-centric networks. In other words, the response data need not be obtained by a specific SN; it only needs to be at a particular time and place. Therefore, if the data was retrieved from a specific area, it might have been replaced

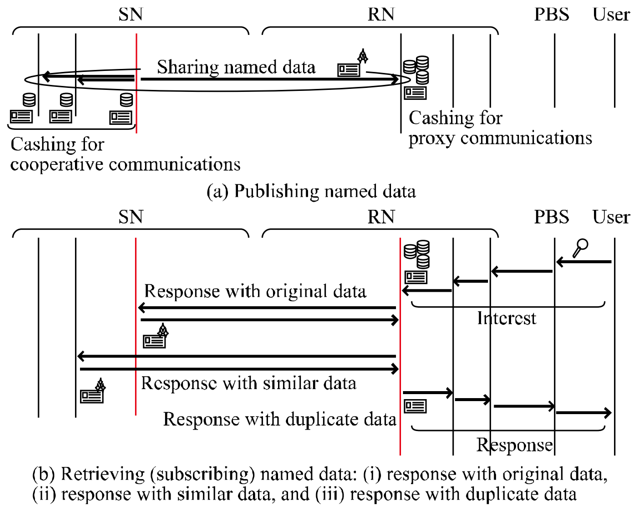


Figure 4. Procedure of data collection and retrieval in proposed scheme

with the neighbor node. If the response can be provided using similar data rather than the original data, it can improve the response probability.

D. PHY/MAC and ICN layers protocol design

The ICN protocol and packet format have been defined in IETF RFCs, such as RFCs 8569 and 8609. Therefore, if the proposed framework is to be used universally and extensively, its format must be fully compliant with existing ICN standards and be formally approved through standardization. This section focuses on the functionalities required to operate ICWSN rather than strict definitions. Note that standardization and related considerations are out of scope, but they will be continuously investigated as part of our future work. This section highlights how the ICN l ayer is stacked on top of the PHY/MAC layer in ICWSNs.

As a network design principle, the ICN layer's data transmission is based on multicast. Specifically, the data retrieval requests (interest) are multicast to the destination specified in the FIB, while the responses are transferred via a multipath-based unicast method according to the PIT. Also, the PHY/MAC layer's wireless communication is an over-the-air (overhearing), flooding-based broadcast method. However, the intermediate layer between them, i.e., a network layer like TCP (UDP)/IP, is sandwiched between them and generally uses a unicast communication method. Therefore, it is necessary to bridge the gap between the upper layer (ICN) and the lower layer (PHY/MAC). Although IP multicast primarily supports UDP-based data streaming applications, such as real-time video broadcasting, the reliability of data transmission over WLANs remains a concern.

For named data, the naming rule, data freshness, and security will be based on the same mechanisms as in the general ICN platform. Since the proposed scheme is designed for regional ICWSNs, using flat addresses is adequate. At the same time, it is necessary to determine a unique conversion rule for each data attribute (such as time and location) within each ICWSN. For data freshness, ICN cannot use the same latency-related parameters as used in conventional networks. This is because the traditional network provides user responses from a fixed server, whereas ICN allows any node that stores cached data to act as a data provider. This aspect is currently under study as a new design based on the Age of Information (AoI) [29]. A detailed discussion regarding this matter is beyond the scope of this paper.

The proposed scheme seeks to resolve this issue by using cross-layer design [30], as shown in Figure 5. Cross-layer design is a methodology that intentionally breaks the traditional layered hierarchy to optimize overall system performance by enabling information sharing and coordinated operations across non-adjacent layers. For instance, the proposed scheme bypasses the middle layer. The cross-layer design presented here can be well-designed and well-explained in purely theoretical and academic settings, but it is not practical. Instead, a practical solution with a practical implementation is outlined as follows. The FIB settings of the unicast-based ICN platform are dynamically configured while considering compatibility; this enables multiple unicast communications to operate in parallel and thereby emulates the behavior of multicast communications. On the other hand, with such a simple design, the data transmission request and the target node generate exponential traffic. This problem can be alleviated by incorporating a proxy caching scheme into the RNs (mesh network). At the same time, the proxy caching scheme can reduce traffic in the wireless communication section by aggregating cached data to a manageable level. This mechanism is the core idea of the cooperative communication scheme described in Section III.A, and it can be enabled through the above alternative approach. A detailed validation, including implementation, network construction, and proof-of-concept demonstrations, remains as future work.

E. Channel allocation and assignment

As a network model based on WLANs, the proposed scheme assumes the use of microwaves (in the 2.4-GHz and 5-GHz bands) and mmWaves (in the 60-GHz band). Microwave WLANs are common, inexpensive commodity systems, making it suitable for the SNs, RNs, and PBS. However, since the mmWave WLAN system is not yet available, it will be used in the RNs and PBS as a backhaul. Moreover, WLANs are commonly standardized, but the available spectrum is regulated by individual countries and regions. As shown in Figure 6, four and 20 microwave channels and four mmWave channels are available in Japan. Note that a practical WLAN system can provide a multiplexing scheme, but here we count the number of non-overlapping wireless channels. In addition, the mmWaves have a 2.16 GHz bandwidth per channel, and high-speed data transmission is performed across the entire frequency band. Here, we suppose a 20 MHz bandwidth per channel for mmWaves, similarly to microwaves; 108 channels are available.

VI. Computer Simulations

The proposed scheme’s feasibility was estimated in terms of its characteristics in the PHY and MAC layers by using computer simulations. In particular, the evaluations focused on whether the system is fundamentally usable, especially its

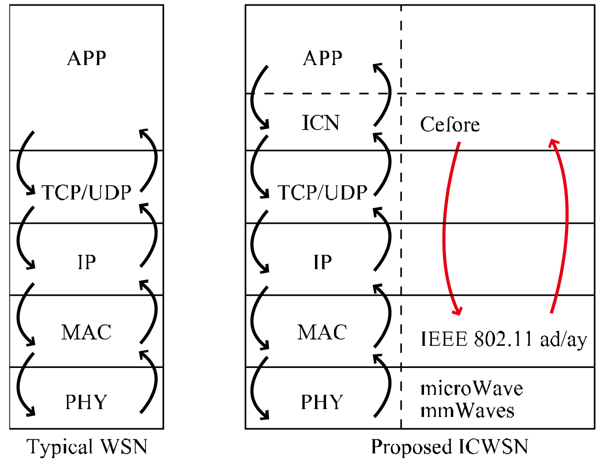


Figure 5. Protocol stack design: Typical WSN versus proposed ICWSN

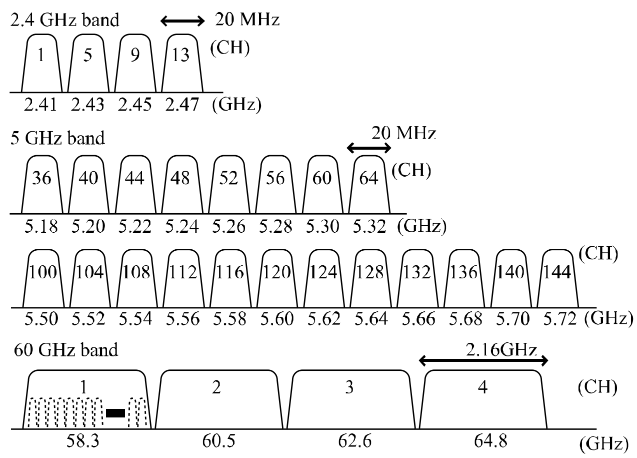


Figure 6. Channel-allocation plan in proposed scheme in compliance with Japan’s regulations

resilience to the network traffic potentially generated by the SNs.

We assumed that the RNs (and PBS) support mmWave connectivity; and are installed in fixed locations, as shown in Figure 7(a). Furthermore, a mesh network based on mmWaves was constructed using four-sided antennas. In accordance with the Terragraph specifications [21][22][23], the communication range was set to 200–300 meters and the MCS index was set to 12 and 9, i.e., the catalog specifications; this would give a communication range of 250 meters. We assumed that the mmWave device could use four channels and that devices in adjacent areas could not use the same channels because of interference. Furthermore, the antenna was directional (beamforming). Given the above constraints, as shown in Figure 7(b), 25 fixed nodes (24 RNs and a PBS) were distributed in a latticed layout, and their channel assignments were determined. Note that if nodes are distributed completely at random, some of them might not be able to reach the PBS. The signal strength of mmWaves varies depending on objects in the surrounding environment, such as farms, trees, humans, and vehicles; i.e., they can be disrupted by intermittent signal interference and obstructions. Here, we assumed a flat, obstacle-free countryside, free of the aforementioned signal disruptions, to simplify the computer simulation.

Figure 7(b) shows the scenario with 100 SNs distributed randomly in the field. Note that the simulation covered scenarios with 100 to 400 SNs. When the communication range was set to 200 m, all SNs were within the coverage area of the RNs. Here, we will call an RN that an SN can access a parent node and call the SNs accommodated by the same RN team nodes. Since RNs can guarantee connectivity to PBS via a mutual mesh network, if any SN can connect directly to the RN (parent node), all SNs remain network members without isolation, making it possible to collect and access the sensing data. The network layout and channel allocation described here enable a broadband wireless video solution, as described in Section III.C.

Figures 8–10 show the simulation results regarding the PHY/MAC layer capacity to support traffic on the ICWSN. The simulations account for the worst-case scenario in which all SNs (100–400) generate call requests simultaneously where they continuously transmit data. In other words, this evaluation is of how tolerant the wireless channel is to multiple SNs sending messages simultaneously. In addition, mutual interference among SNs was considered, but the channel allocation was performed ideally. Figure 8 shows the offered load divided by the capacity for all relay nodes as a statistical Cumulative Distribution Function (CDF). Since the offered load over the capacity was for a simulated environment, it was calculated by assuming up to twice the actual channel capacity that could be utilized. Here, when 100 SNs were simulated, the offered load over the capacity for all RNs was 72%, indicating sufficient wireless resources. However, wireless capacity was insufficient in the other cases (200, 300, and 400 SNs), resulting in a significant reduction in data transmission performance (offered load over capacities of 112%, 120%, and 140%, respectively).

Figure 9 shows a heatmap of overall wireless channel occupancy rates in the ICWSN field for the microwave spectrum. The results indicate high channel occupancy in the central field area. In contrast, Figure 10 indicates that millimeter-wave relay stations can sufficiently accommodate the traffic generated by 100–400 SNs because mmWaves can use a larger bandwidth (4.5 times as many channels as microwaves). Note that the fan-shaped radiation patterns in Figure 10 are due to directionality, and the fixed orientations are caused by the fixed routing path shown in Figure 7. Overall, these results indicate that it is necessary to determine the placement of nodes in the field.

VII. Conclusion

We presented a blueprint of the ICWSN platform for smart agriculture. The proposed platform integrates ICN, WSN, mmWaves, AI, and related technologies. The system design for implementing the platform was presented and preliminary evaluations were conducted.

In future work, we will carry out our plans and expect to achieve our goals. In particular, regarding the proof of concept for the network construction, it will be necessary to ensure

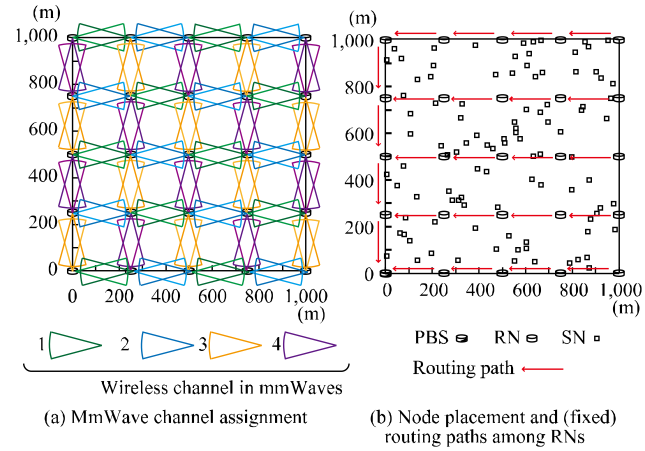


Figure 7. MmWave channel allocation and node placement

sufficient coverage to support the development of the network ecosystem. In addition, we will demonstrate the scalability and extensibility of the proposed scheme which is expected to operate stably for medium- to long-term periods. Furthermore, the platform developed in this research project will be used for other smart-city applications. In addition, it will be necessary to consider a broadcast-based wireless communication system combining ICN and WSN for edge-side networks. On the basis of the strategies identified in this study, the requirements for the key elemental technologies must be provided as feedback, including limitations and potential challenges.

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References

[1] S. Mori, "Concept of ecosystem for smart agriculture: Millimeter-wave information-centric wireless visual sensor network," *Proc. IARIA IARIA Congress*, pp. 33–37, Venice, Italy, July 2025.

[2] B. Ahlgren, C. Dannewitz, C. Imbrenda, D. Kutscher, and B. Ohlman, "A survey of information-centric networking," *IEEE Commun. Mag.*, vol. 50, no. 7, pp. 26–36, July 2012.

[3] M. Zhang, H. Luo, and H. Zhang, "A survey of caching mechanisms in information-centric networking," *IEEE Commun. Surveys & Tutorials*, vol. 17, no. 3, pp. 1473–1499, Apr. 2015.

[4] S. Mori, "Fundamental analysis of cooperative communication scheme using hierarchical modulation for information-centric wireless sensor networks," *Proc. IEEE CCNC 2025*, Las Vegas, USA, Jan. 2025 pp. 1–2, doi: 10.1109/CCNC54725.2025.10976088.

[5] N. Victor et al., "Remote sensing for agriculture in the era of industry 5.0—A survey," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 17, pp. 5920–5945, Feb. 2024.

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

[7] M. Bilal and S. G. Kang, "Network-coding approach for information-centric networking," *IEEE Systems Journal*, vol. 13, no. 2, pp. 1376–1385, June 2019.

[8] J. Llorca, A. M. Tulino, K. Guan, and D. C. Kilper, "Network-coded caching-aided multicast for efficient content delivery," *Proc. IEEE ICC 2013*, Budapest, Hungary, June 2013, pp. 3557–3562, doi: 10. 1109/ICC.2013.6655103.

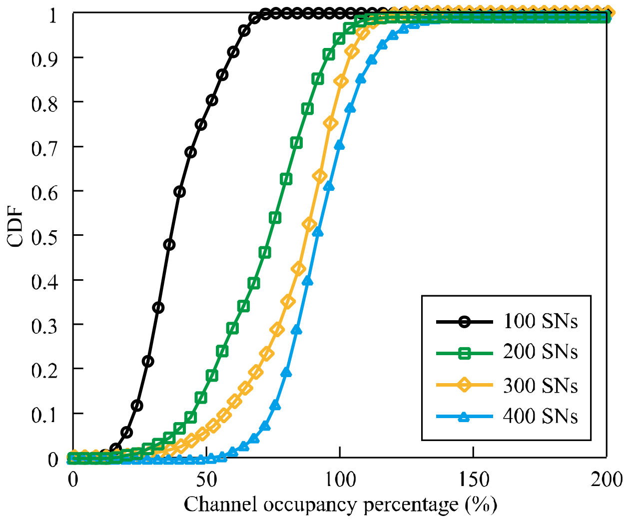

Figure 8. Statistical charactristics of channel occupancy in microWaves

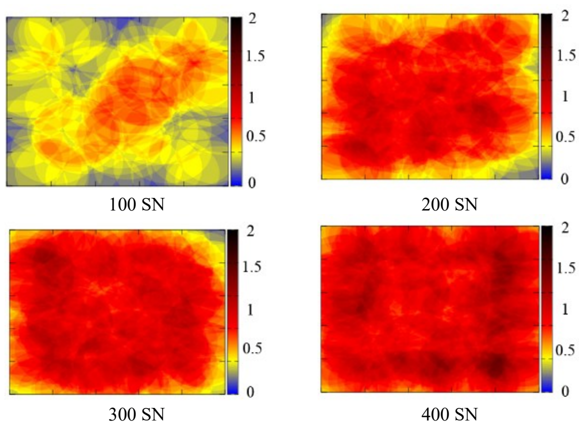

Figure 9. Heatmap of ICWSN deployment field in microWaves

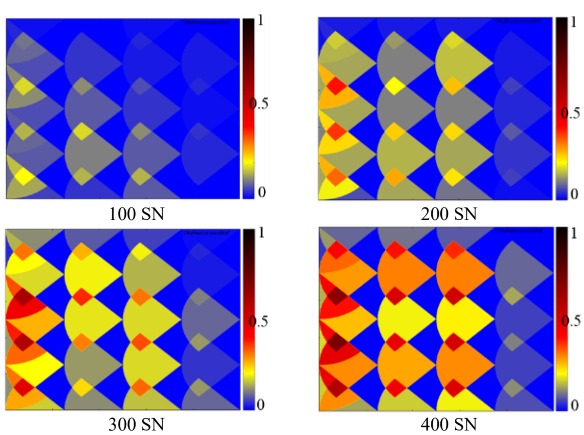

Figure 10. Heatmap of ICWSN deployment field in mmWaves

[9] A. Ramakrishnan, C. Westphal, and J. Saltarin, “Adaptive video streaming over CCN with network coding for seamless mobility,” *Proc. IEEE ISM 2016*, San Jose, USA, Dec. 2016, pp. 238–242, doi: 10.1109/ISM.2016.0054.

[10] Y. Yang and T. Song, “Energy-efficient cooperative caching for information-centric wireless sensor networking,” *IEEE Internet of Things Journal*, vol. 9, no. 2, pp. 846–857, Jan. 2022.

[11] J. Yin, et al., “On the network coding-based D2D cooperative recovery for lossy feedback-free broadcasting,” *IEEE Commun. Letters*, vol. 27, no. 9, pp. 2283–2287, Sept. 2023.

[12] D. You, Y. H. Lee, S. H. Choi, D. H. Kim, and S. Cho, “Joint hierarchical modulation and network coding for asymmetric data rate transmission over multiple-access relay channel,” *Proc. ICUFN 2016*, Vienna, Austria, July 2016, pp. 96–98, doi: 10.1109/ICUFN.2016.7536991.

[13] M. Tang, J. Chen, Y. Zhang, and Y. Zhang, “Performance analysis for physical-layer network coding with hierarchical modulation,” *Proc. IEEE ICCSN 2016*, Beijing, China, June 2016, pp. 33–37, doi: 10.1109/ICCSN.2016.7586682.

[14] S. Tharranetharan and M. J. Hossain, “A hierarchical modulation and network coding-assisted BICM system for asymmetric two way relay channels,” *Proc. IEEE VTC2014-Fall*, Vancouver, Canada, Sept. 2014, pp. 1–5, doi: 10.1109/VTCFall.2014.6965815.

[15] 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.

[16] 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.

[17] Terragrah, https://terragraph.com/ (retrieved: May 2026).

[18] 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.

[19] S. Mori, “A cooperative and coded communication scheme using network coding and constructive interference for information-centric wireless sensor networks,” *International Journal on Advances in Networks and Services*, vol. 15, no. 3&4, pp. 54–61, Dec. 2022.

[20] S. Mori, “Zero-touch-design information-centric wireless sensor networking with availability assurance,” *International Journal on Advances in Networks and Services*, vol. 16, no. 3&4, pp. 63–74, Dec. 2023.

[21] BeMap, https://www.bemap.co.jp/ (retrieved: May 2026).

[22] S. Mori, “Millimeter-wave information-centric wireless-sensor-network ecosystem: Evaluation under non-terrestrial environment and demonstration in actual city,” *International Journal on Advances in Networks and Services*, vol. 18, no. 3&4, pp. 81–89, Dec. 2025.

[23] 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.

[24] Cefore, https://github.com/cefore/cefore/ (retrieved: May 2026).

[25] YOLO, https://ultralytics.com/ (retrieved: May 2026).

[26] 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.

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

[28] 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.

[29] S. Mori, “A study on delay-sensitive information-centric wireless sensor and actuator/actor networks,” *Proc. IARIA ICN 2026*, pp. 1–5, Venice, Italy, May 2026.

[30] V. Srivastava and M. Motani, “Cross-layer design: A survey and the road ahead,” *IEEE Commun. Mag.*, vol. 43, no. 12, pp. 112–119, Dec. 2005.