ICNRG@IETF125
Remote (Tokyo)

Information-centric wireless-sensor-network platform development in mmWave-band communications

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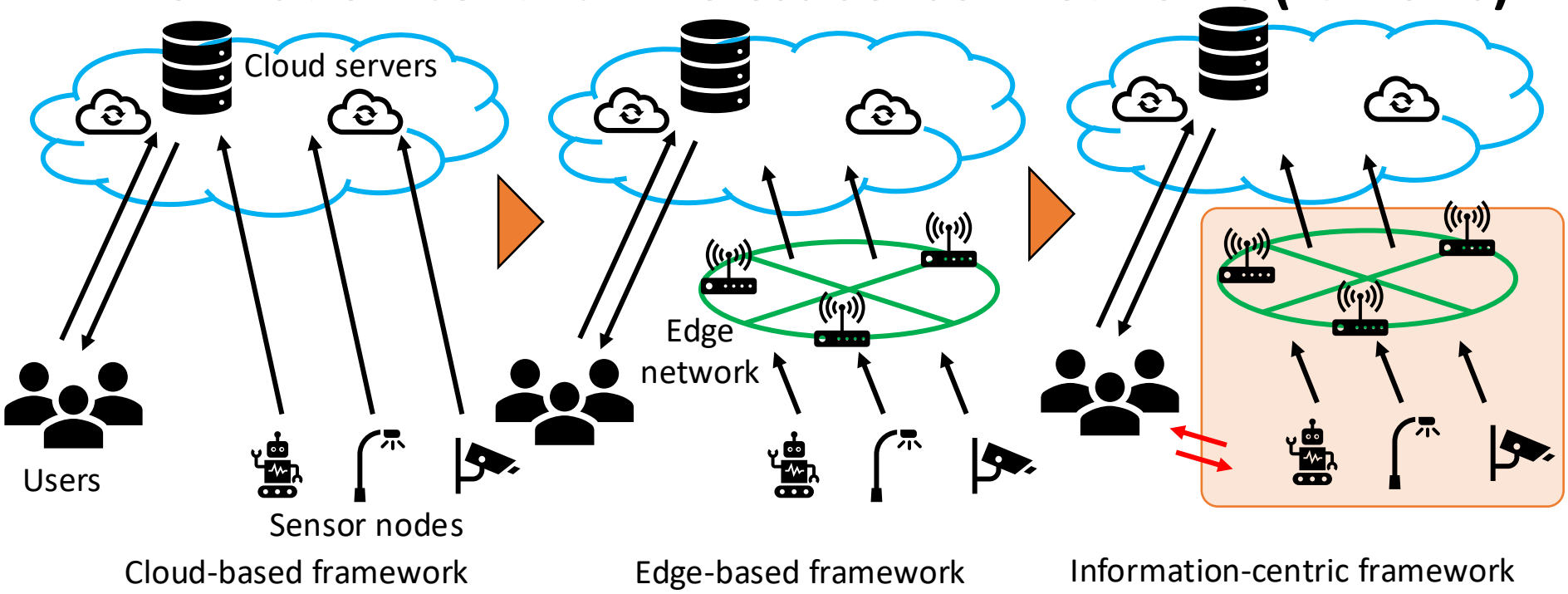
人をつくり、時代を拓く。
福岡大學
R!se with US
Fukuoka University

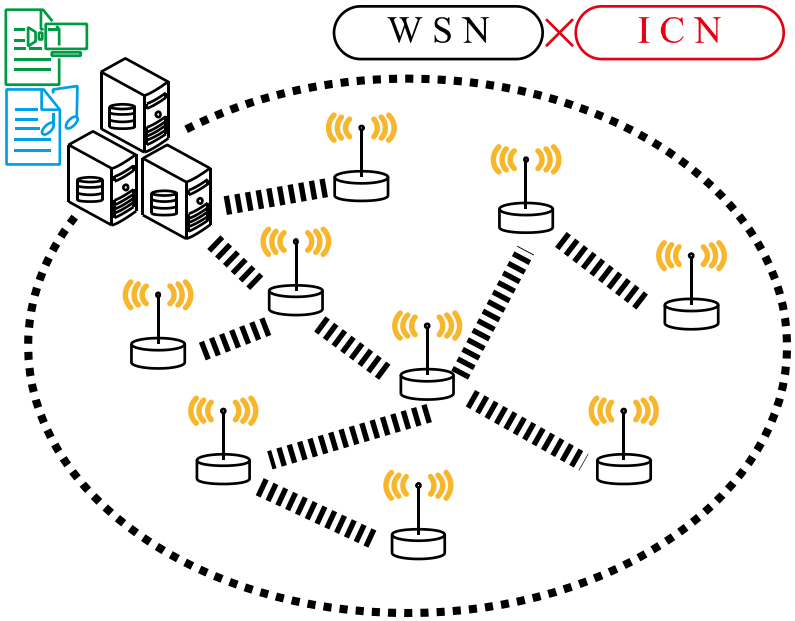
This work was partly supported by JSPS KAKENHI Grant Number 25K15104.

Information-centric wireless sensor networks (ICWSNs)[2]

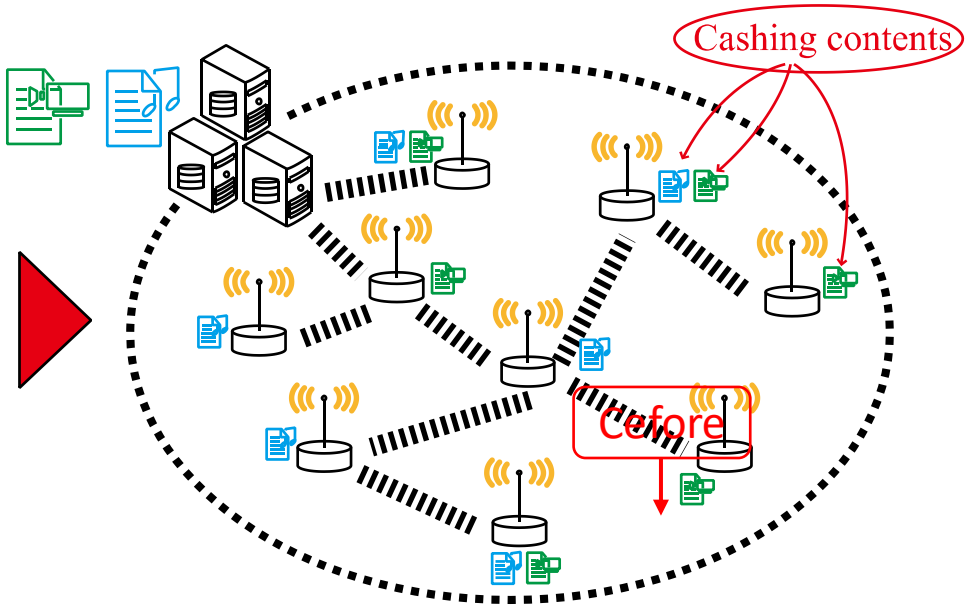


- Internet of Things (IoT) frameworks shift from clouds to edge-side nodes.
  - To improve response time (latency), several functions and data (storage) are migrated from cloud servers to edge (fog) nodes.
  - The framework must be designed for autonomous and distributed environments.
- Integrating Wireless sensor networks (WSNs) and information-centric networking (ICN)
  - ICWSN can improve efficiency, latency, and energy consumption.
  - ICWSN can support pull-style, i.e., data retrieval occurs as needed.
  - The protocol abstraction is reasonable for heterogeneous wireless environments.

ICN meets WSNs

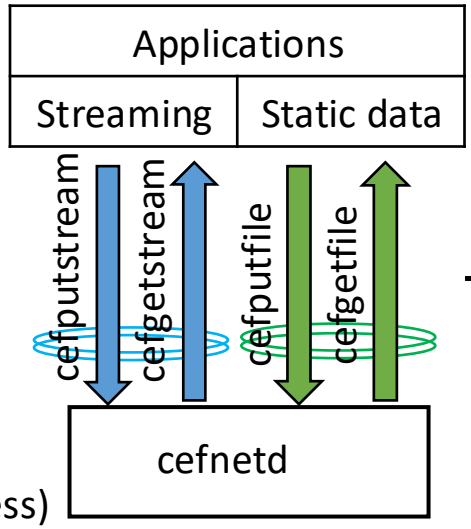


Host-centric network

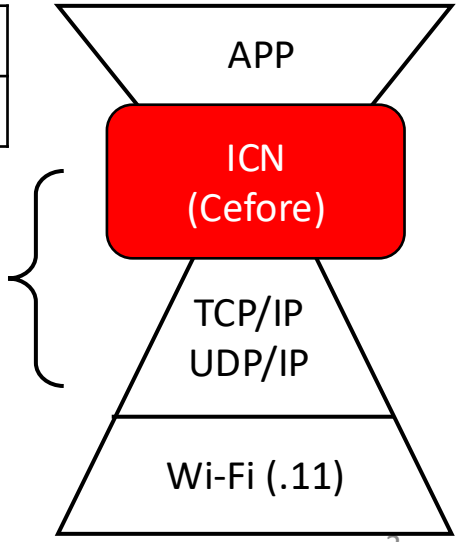


Information-centric network

- We would like to introduce the ICN into WSNs.
- We use Cefore as an ICN platform.

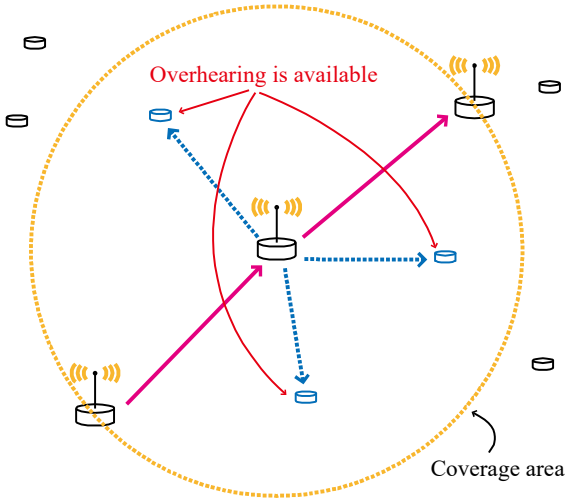


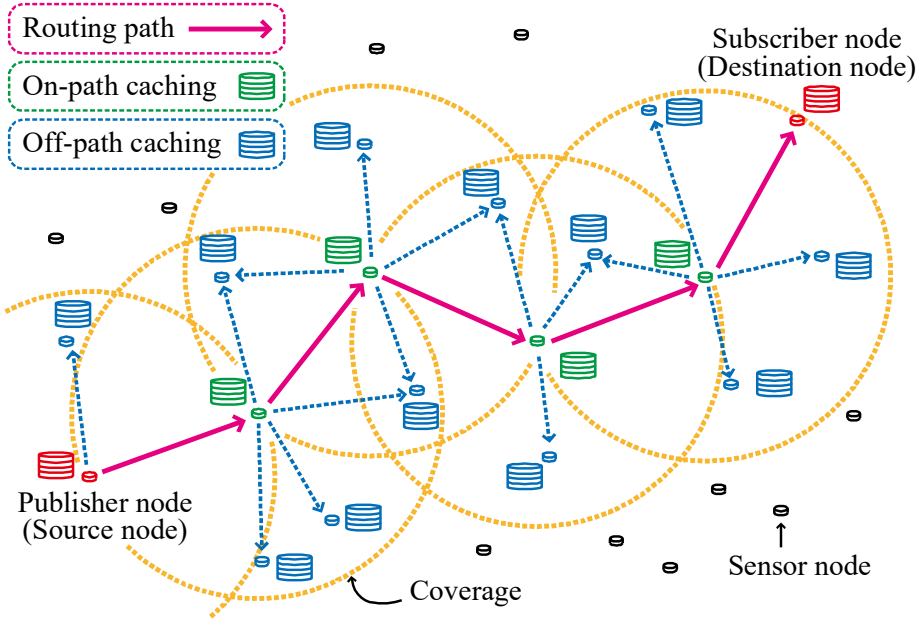
Cefore (deamon process)

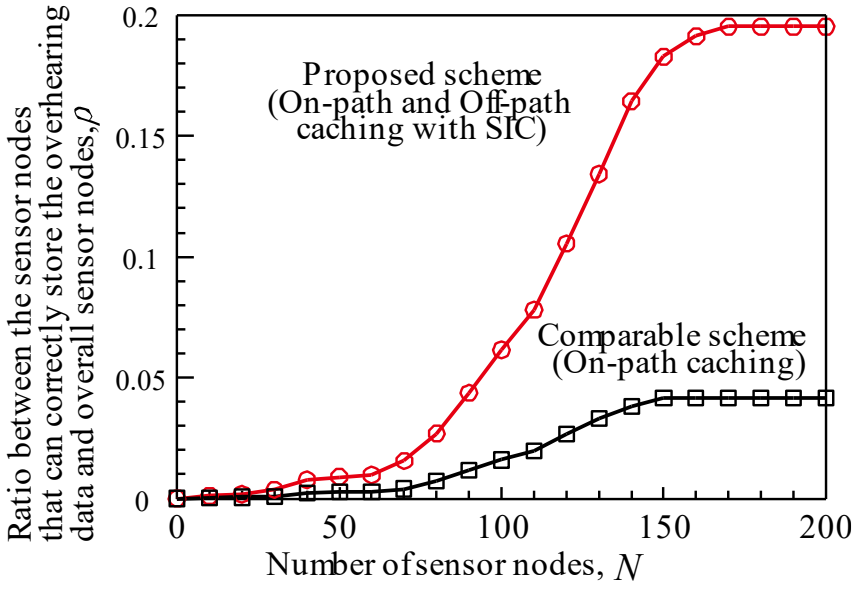


Effective caching scheme

- When a relay node wirelessly forwards the data, neighbor nodes can also receive it [1].
- Using the overhearing phenomenon, we proposed a scheme in which the nodes outside the route will actively cache.
- The proposed scheme achieves off-path caching without any particular mechanism by using wireless communication features.



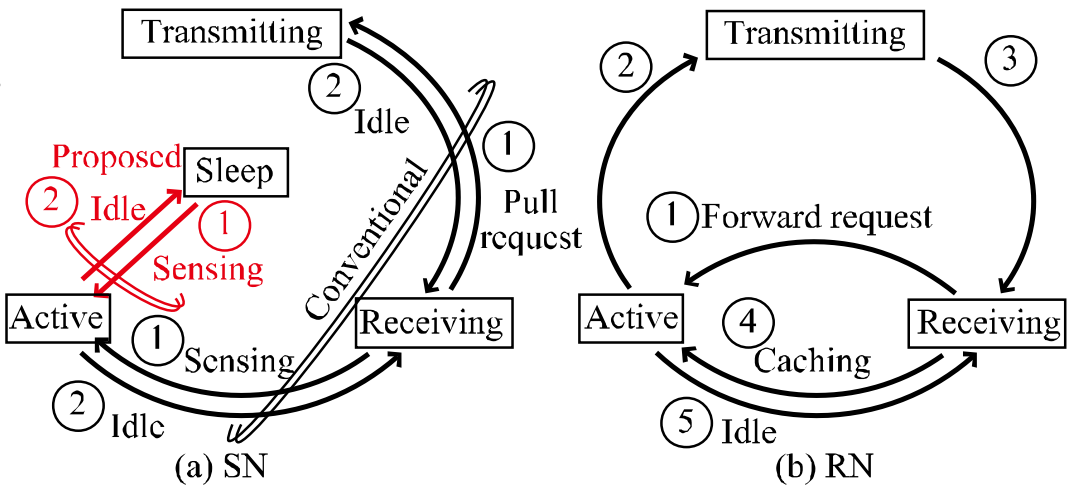




[1] S. Mori, "A study on off-path caching scheme by using successive interference cancellation for information-centric network-based wireless sensor network," *Proc. IARIA ICN2017*, pp. 42–45, Venice, Italy, Apr. 2017.

Green ICWSNs for sustainable smart city

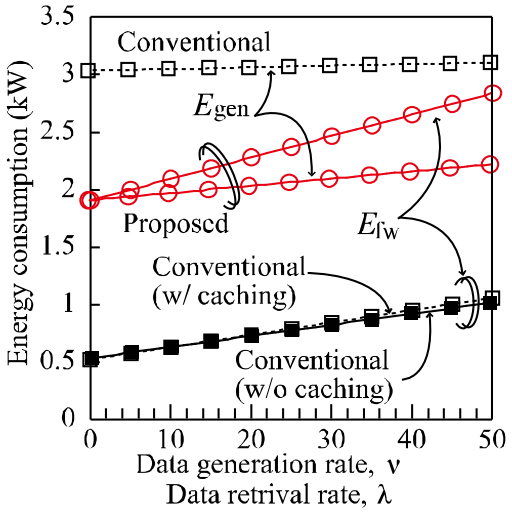
- In our studies†, we formulate the energy consumption model.
- The node switches four possible states, as shown in the state-transition diagram.
- Letting e denotes energy consumption per time of ΔT.
- In the proposed scheme, we use the technique as follows:

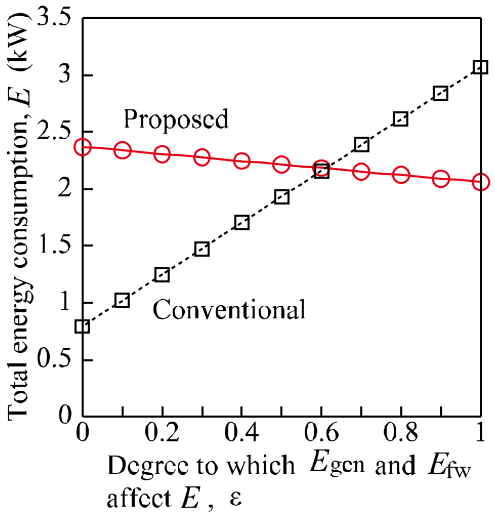


- On-path and off-path caching methods: ICWSNs can overhear the data, improving the hit probability of data retrieval.
- Proxy caching method: The relay nodes take over the response from responding neighbor nodes; as a result, the nodes can switch to the sleep or standby state to reduce energy consumption.

† S. Mori, "A preliminary analysis of data collection and retrieval scheme for green ICWSNs," *Proc. ACM SIGCOMM WS NET4us*, 2022.
† S. Mori, "Energy-efficient cooperative caching scheme for Green ICWSN: Preliminary analysis and testbed development," *Proc. ACM MobiCom WS NET4us*, 2023.

Numerical results regarding Green ICWSN





$$E_{\text{gen}}^{\text{conv}} = \sum_{N_S N_R} \int_T \nu e_A \Delta T + (1 - \nu \Delta T) e_R \, d\Delta T$$

$$E_{\text{gen}}^{\text{prop}} = \sum_{N_S N_R} \int_T \nu (e_A + e_T) \Delta T + (1 - 2\nu \Delta T) e_S d\Delta T$$

(w/o caching)

$$E_{\text{fw}}^{\text{conv}} = \sum_{N_S} \int_T \lambda (e_A + e_T) \Delta T + (1 - \lambda \Delta T) e_R \, d\Delta T + \sum_{N_S} \int_T \alpha \lambda e_T \Delta T + (1 - \lambda \Delta T) e_R \, d\Delta T$$

(w/ caching)

$$E_{\text{fw}}^{\text{conv}} = \sum_{N_S} \int_T \lambda (e_A + e_T) \Delta T + (1 - \lambda \Delta T) e_R \, d\Delta T$$

$$E_{\text{fw}}^{\text{prop}} = \sum_{N_S} \int_T e_S \, d\Delta T + \sum_{N_S} \int_T \alpha \beta \lambda (2e_A + e_T) \Delta T + (1 - \lambda \Delta T) e_R d\Delta T$$

$$E = \varepsilon E_{\text{gen}} + (1 - \varepsilon) E_{\text{fw}}$$

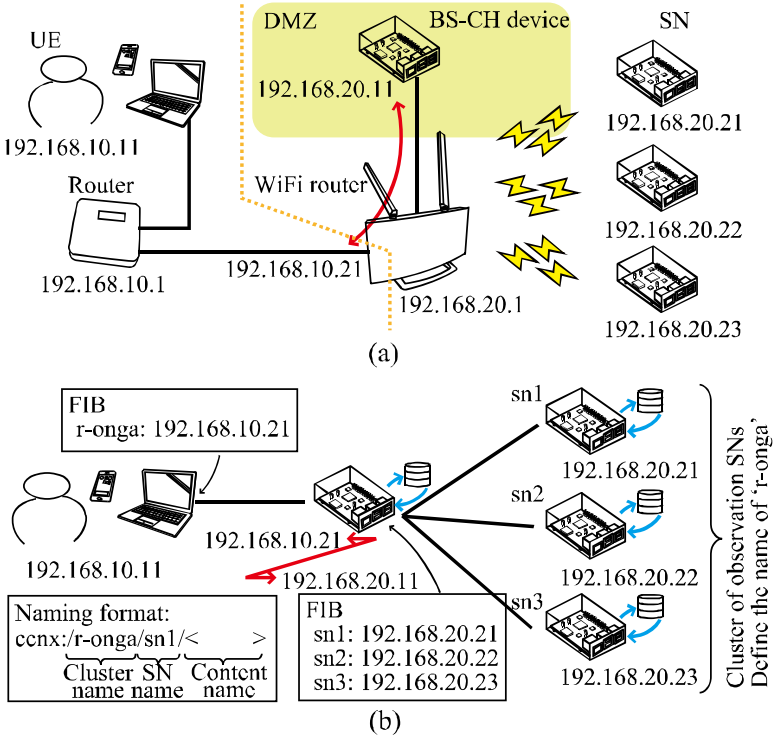
- Simulation environments:
  - Computer simulators were implemented using C++.
  - The nodes were randomly distributed across the area.
  - The simulation was considered the worst case.
- Simulation results:
  - The results indicated that the proposed scheme was effective for the lower frequency of data generation and data retrieval environment.

Simulation parameters

Terms	Values
Area	1 km^2
Number of nodes	N_S: 1,000 N_R: 0–200
Consumed energy	e_S: 1.63 W e_R: 2.76 W e_A: 3.98 W e_T: 4.66 W

Wireless communication and network technologies for ICWSNs.

- We implemented the testbed to evaluate the applicability of ICWSNs in the river monitoring system [15].
- We used Cefore [16] as an ICN platform in the system.

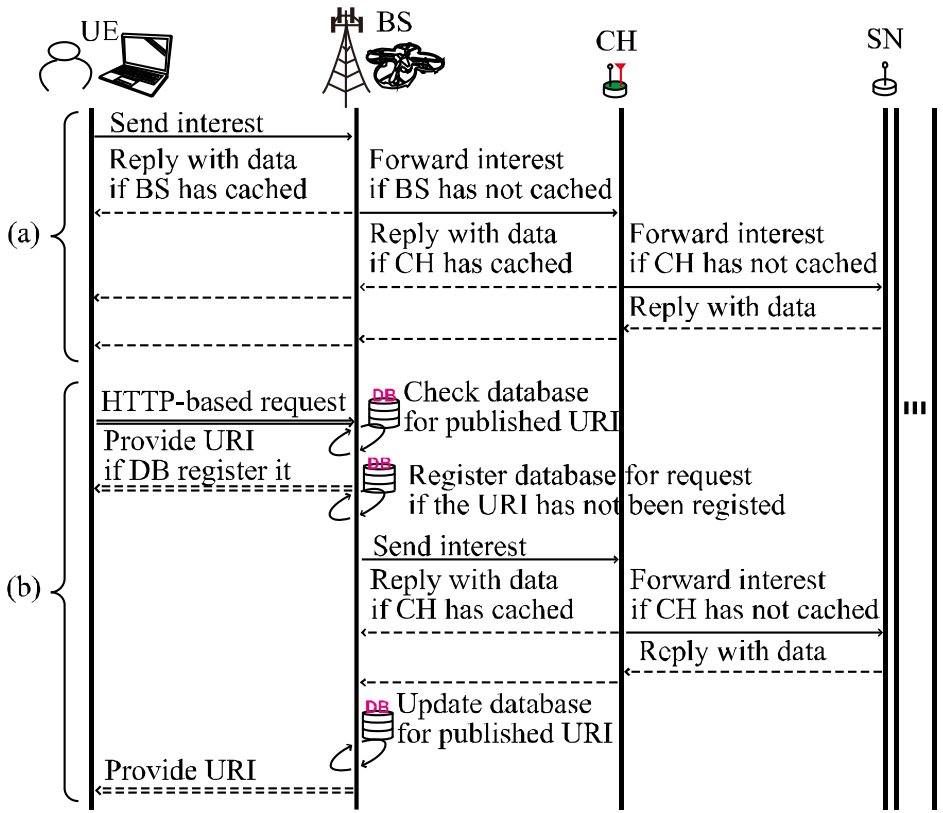


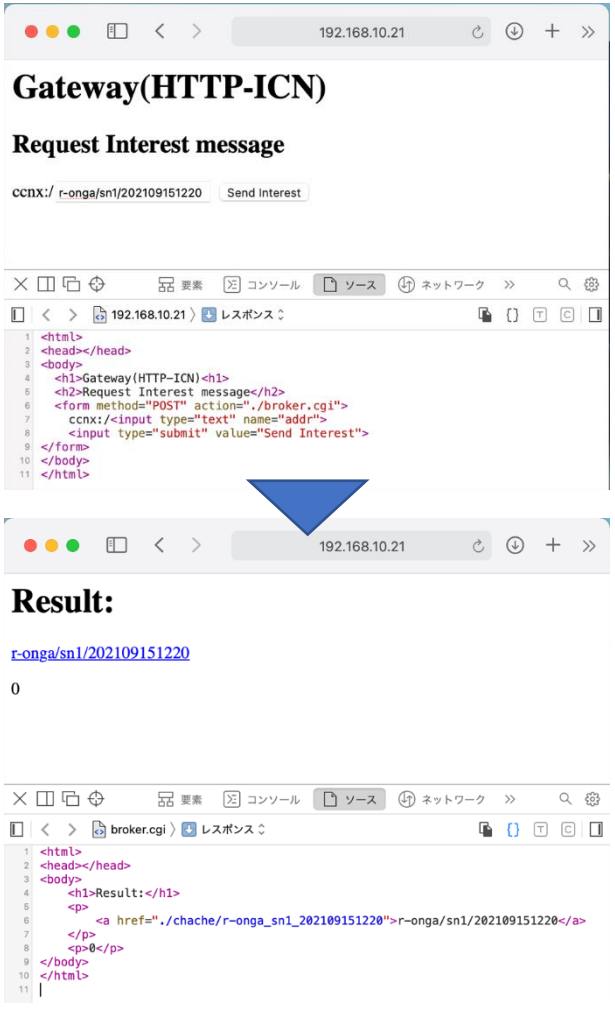
[15] S. Mori, "Data collection scheme using erasure code and cooperative communication for deployment of smart cities in information-centric wireless sensor networks," *Int. J. Advances in Networks and Services*, vol. 14, no. 3&4, pp. 54–64, Dec. 2021.

[16] Cefore: https://cefore.net (retrieved: July 2022).

Wireless communication and network technologies for ICWSNs.

- The proposed system [15] was equipped with a gateway to ensure compatibility even if the API-based systems were coexisting.

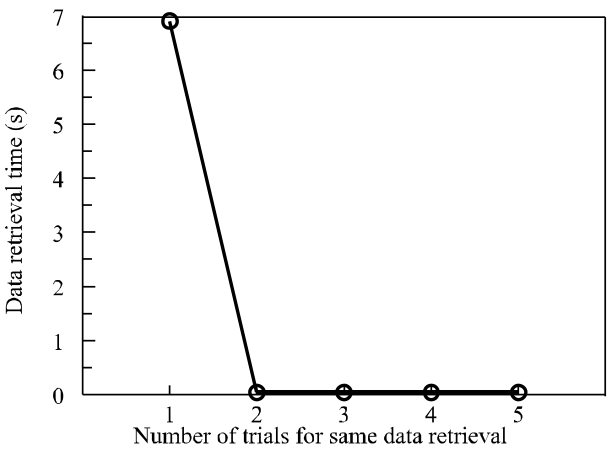




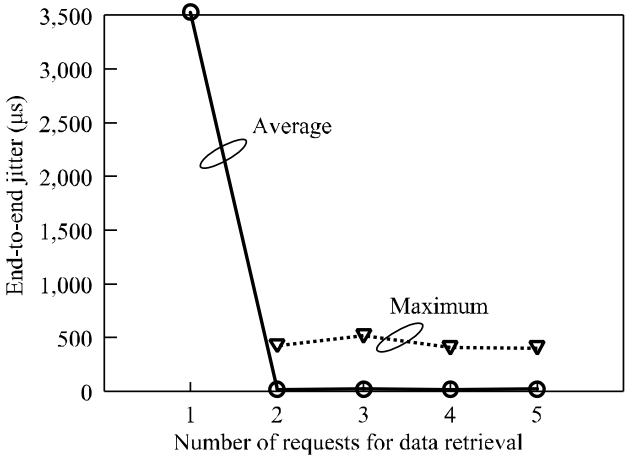
[15] S. Mori, "Data collection scheme using erasure code and cooperative communication for deployment of smart cities in information-centric wireless sensor networks," *Int. J. Advances in Networks and Services*, vol. 14, no. 3&4, pp. 54–64, Dec. 2021.

Wireless communication and network technologies for ICWSNs.

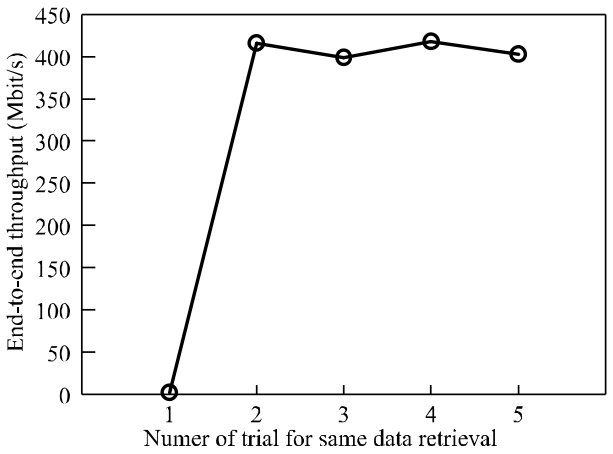
- Thanks to ICN's cache scheme, data retrieval can work stably.
- We have finished the laboratory-based operation test (feasibility).
- This study is in the phase of evaluating an actual field.
- Experimental result of network performance when retrieving the same content [15]:



Data retrieval time



Average jitter



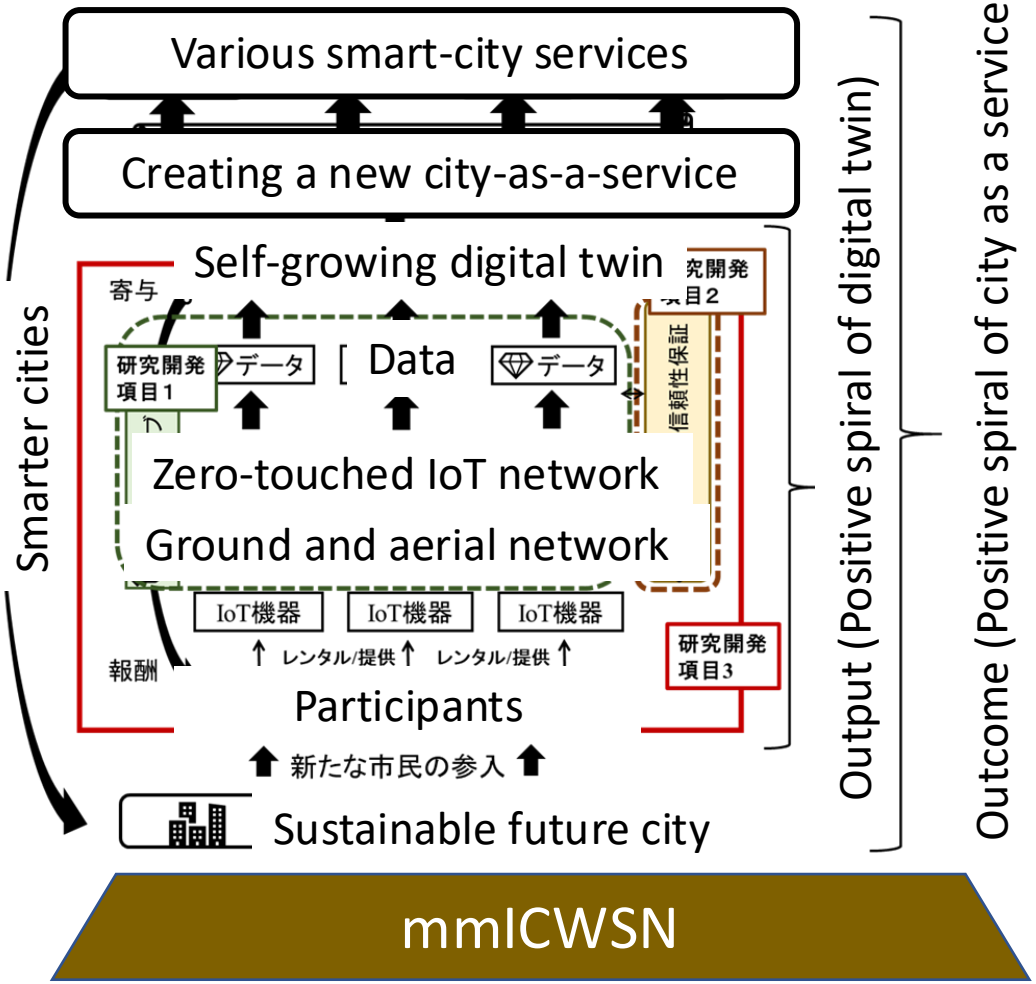
Average throughput

[15] S. Mori, "Data collection scheme using erasure code and cooperative communication for deployment of smart cities in information-centric wireless sensor networks," *Int. J. Advances in Networks and Services*, vol. 14, no. 3&4, pp. 54–64, Dec. 2021.

Ecosystem for smart-city-as-a-service

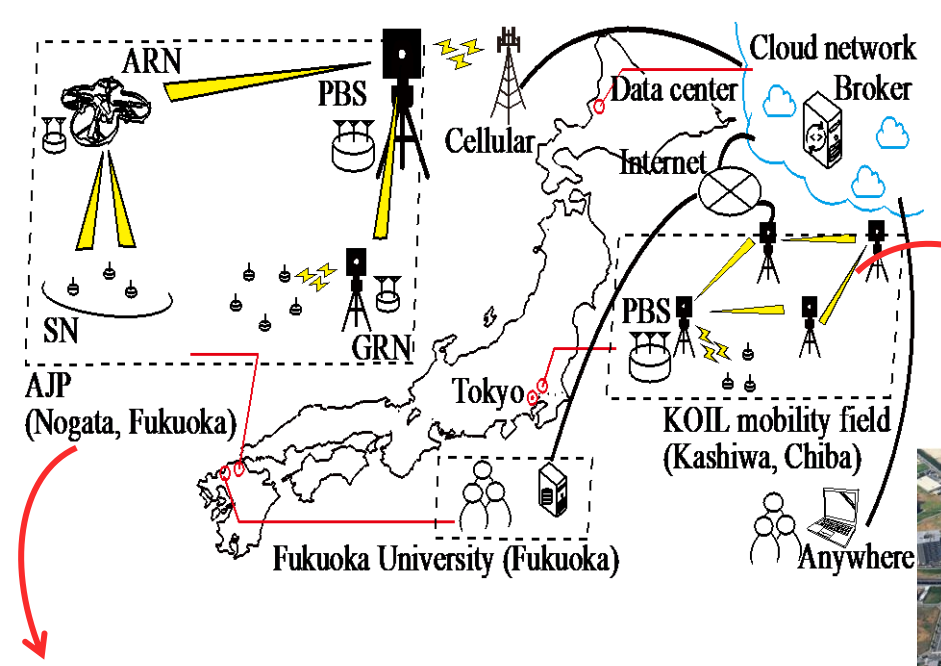
- In our previous research project[4], the decentralized digital twins' ecosystem (D2EcoSys) have been developed.
- In particular, the proposed Wireless Sensor Network (WSN) platform was designed based on ICN and mmWaves, named mmICWSN.

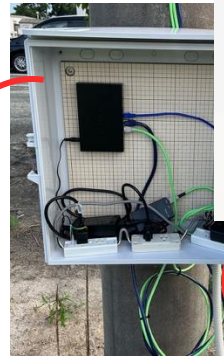
- In detailed,
  - Test-field development
  - Long-term operational testing
  - Long-distance mmWaves experiment in real city
  - Non-terrestrial mmWaves experiment in the test field
  - Real-time vide streaming testing



[4] 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. (Best tutorial paper award)

Proposed mmICWSN framework and its test-field view

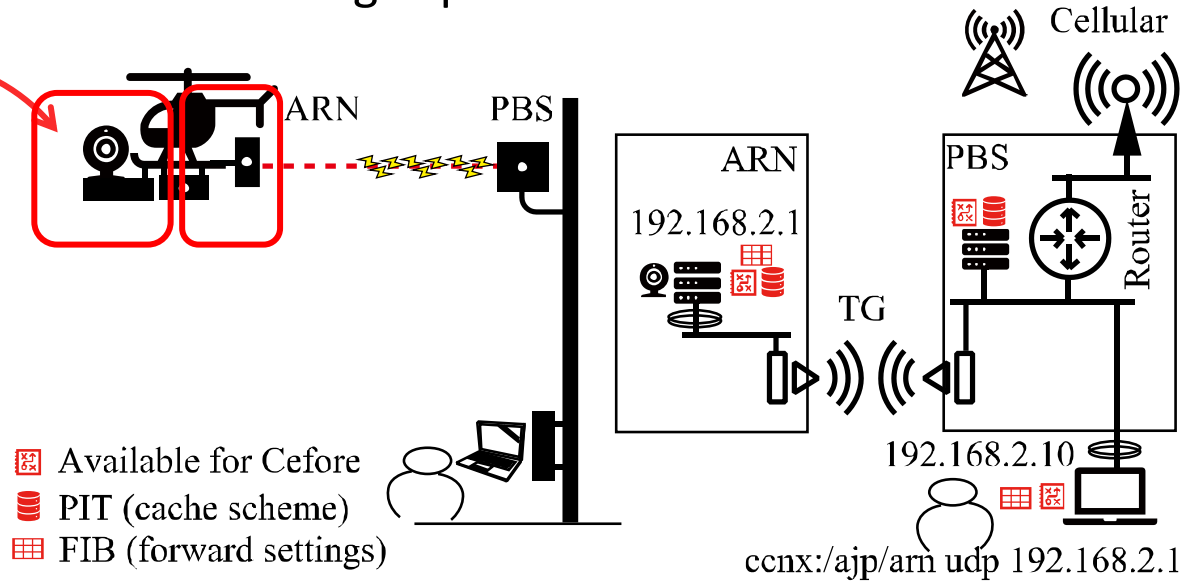




[6] S. Mori, “Test-field development for ICWSNs and preliminary evaluation for mmWave-band wireless communications,” *Proc. IEEE CCNC 2024*, pp. 1–2, Las Vegas, USA, Jan. 2024.

Experimental results: Non-terrestrial environment

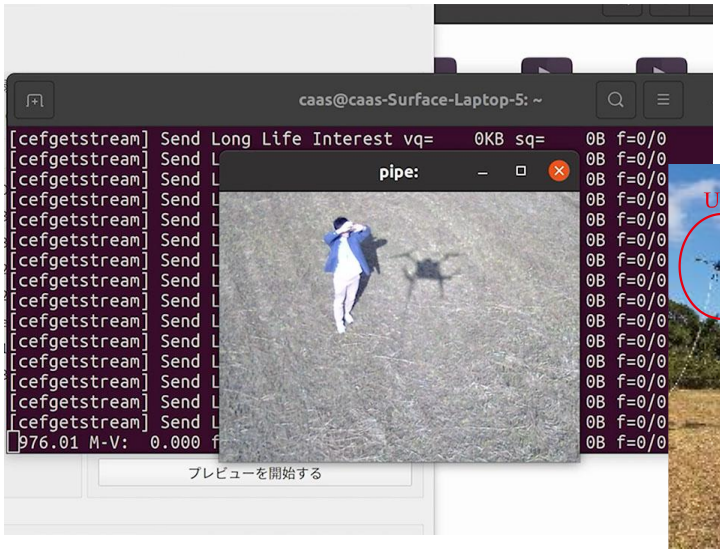
- Network characteristics and video-streaming experiments were conducted.

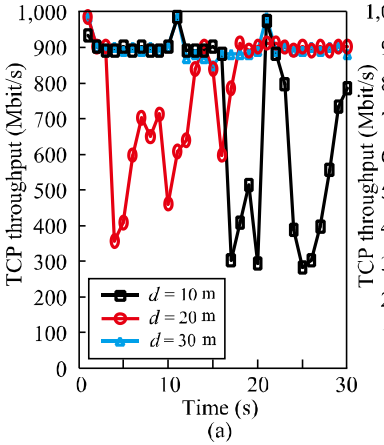


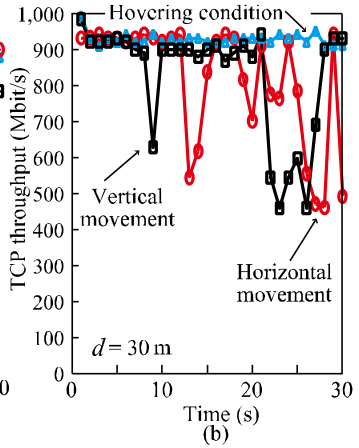
- Aerial node was implemented using industrial drone.
- The photograph shows an overview of the aerial relay nodes (ARN), which comprises a customized BUD device, camera, and Terragraph/CN mounted on the drone.
- The CN/DN pair was connected between the PBS and ARN, with their antenna surfaces facing each other.

[9] Shintaro 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.

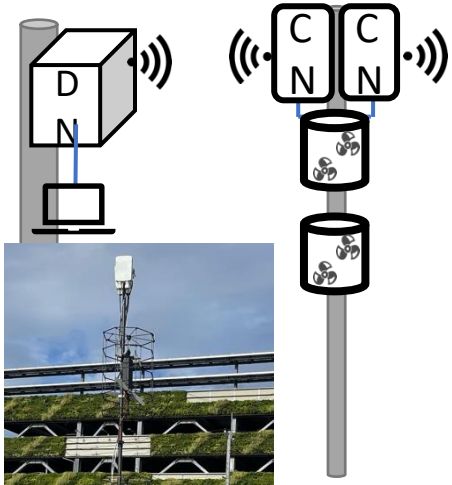
Experimental results: Real-time vide streaming testing

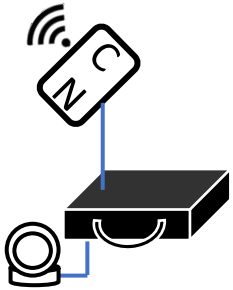






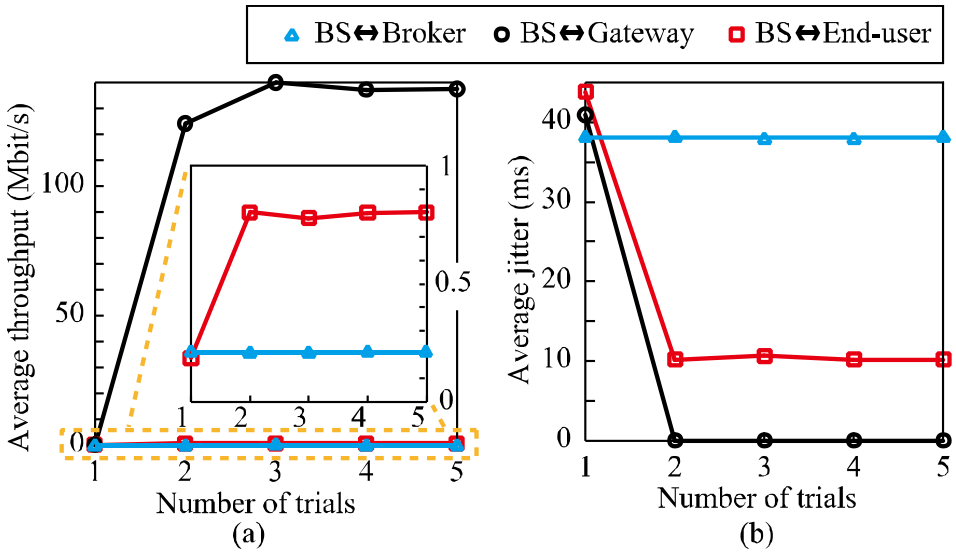
- Real-time video transmissions:
  - In single-hop experiment, the drone was utilized.
  - In multi-hop experiment, the smart poles were used, which can replace air-bone (drone) nodes.

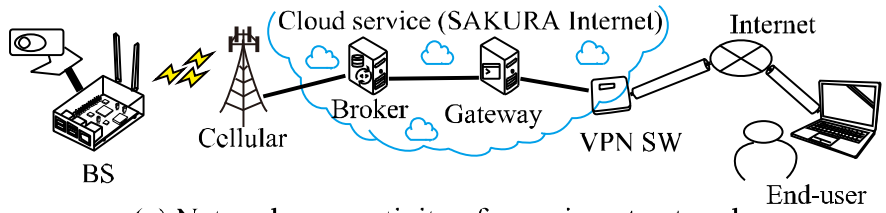




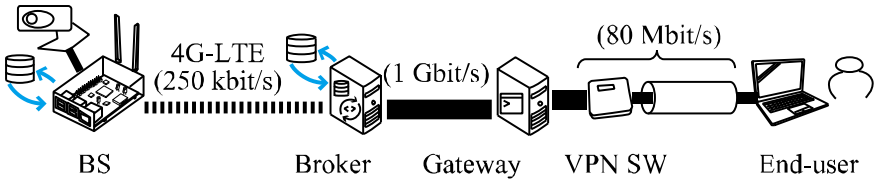
[9] Shintaro Mori, “Millimeter-wave information-centric wireless-sensor-network ecosystem: Evaluation under non-terrestrial environment and demonstration in actual city,” *International Journal On Advances in Networks and Services*, vol. 18, no. 3&4, pp. 81–89, Dec. 2025.

Numerical results: Testbed implementation





(a) Network connectivity of experiment network



(b) Network components and links of ICN framework

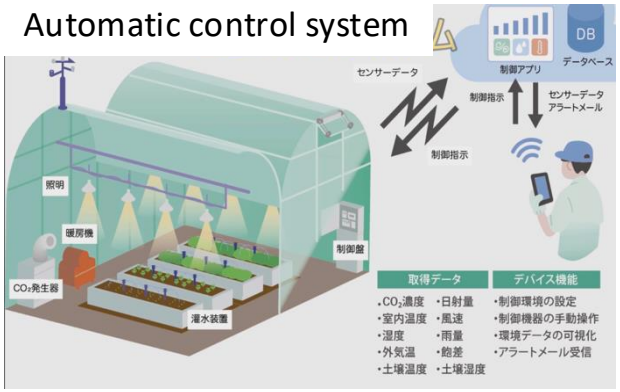
- Figures show network performance, including throughput and jitter.
  - For all three sections, we tried to acquire the same data for five trials.
  - In the experiment, the transmitter-side node was fixed to BS, and the receiver-side node was measured for as the broker, gateway, and end-user.
- The reason behind this improvement was that the data were cached in the broker, and the second or later data retrievals were provided from the broker's cache memory.

Throughput Jitter	1st trial	After 2nd trials
BS~ Gateway	0.202 Mbit/s 40.0 ms	135Mbit/s 0.0624 ms
BS~ End-user	0.186 Mbit/s 43.8 ms	0.797 10.3 ms

Overview of smart-agriculture project

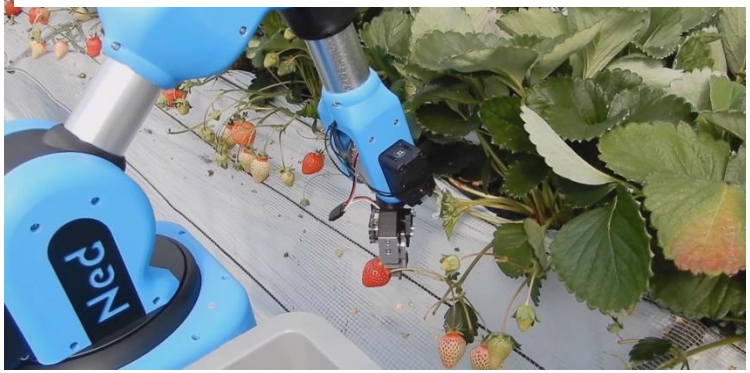
- We developed a smart-agriculture system and applications
  - Remote monitoring and auto-control system for greenhouse
  - Strawberry automatic harvesting robot
  - Security management and pest prevention system for farms

Automatic control system



Remote Monitoring and Automated Control of Plastic Greenhouses

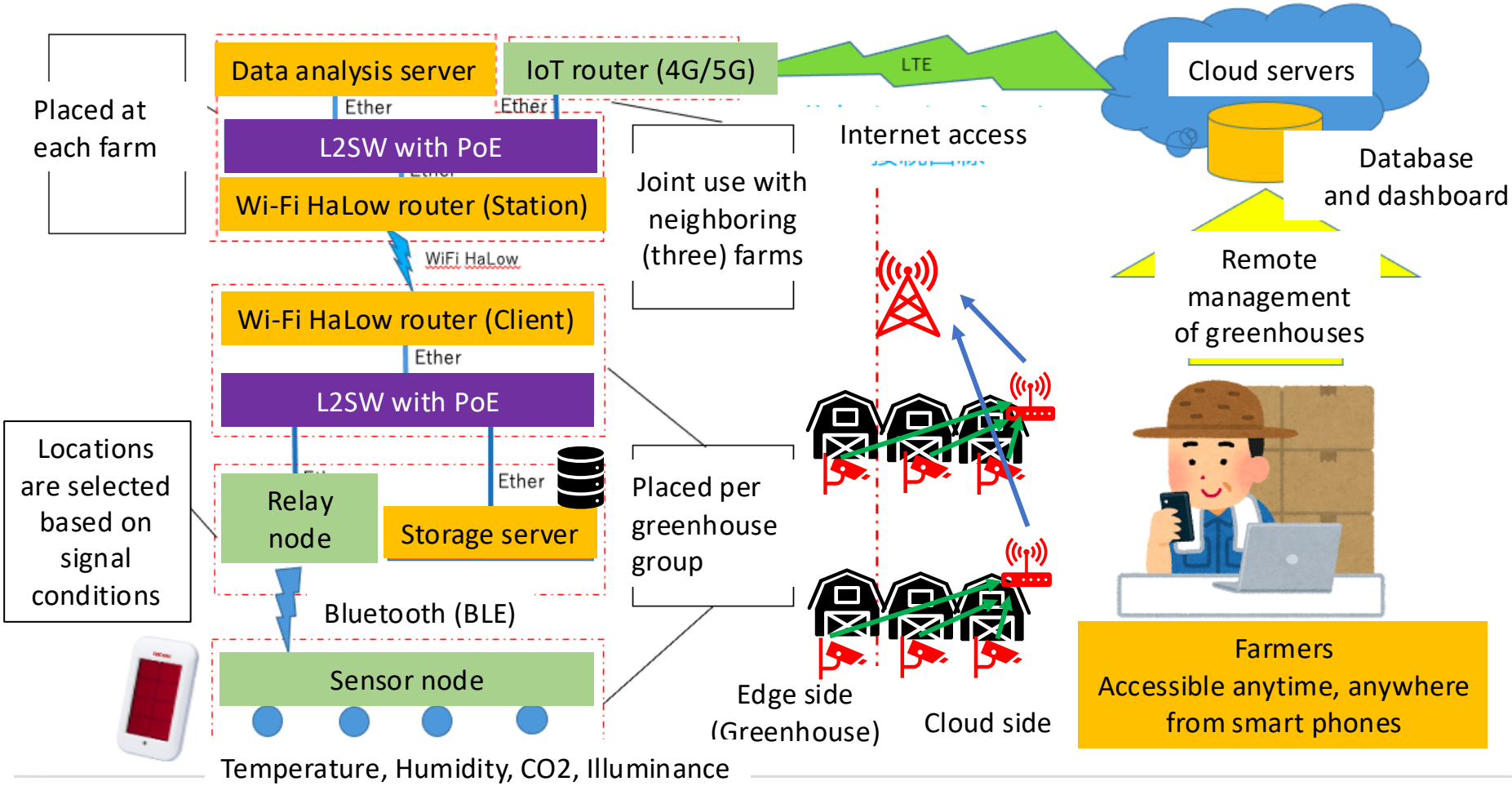
Reducing the burden of harvesting work by harvesting robots



総務省令和6年度 地域デジタル基盤活用推進事業
Ministry of internal affairs and communications
Wi-Fi HaLow・Wi-Fi 6Eを活用したIoT/AIによる農作業自動化システムの構築実証
Demonstration of IoT/AI-based Agricultural Automation System Utilizing Wi-Fi HaLow and Wi-Fi 6E
Final Report (in Japanese)
https://www.soumu.go.jp/main_content/001004674.pdf
https://www.soumu.go.jp/main_content/001004702.pdf
https://www.soumu.go.jp/main_content/001050846.pdf
(retrieved: Mar. 2026)

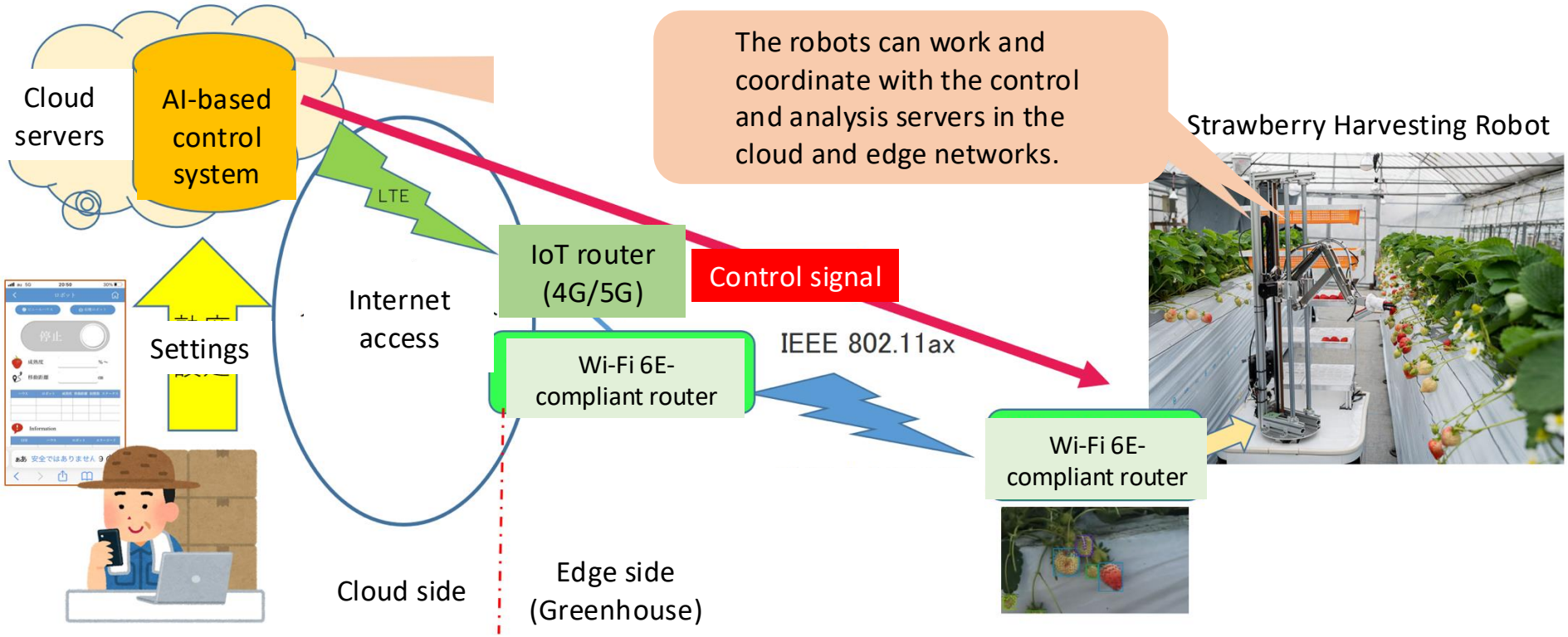
Remote monitoring and control system for greenhouse

- The system can transmit text-based sensing data, but it cannot manage real-time and multimedia data, such as videos and (high-resolution) images.
- Sensing data must be continuously sent to the cloud server, but we can achieve higher efficiency by implementing a pull-based design.



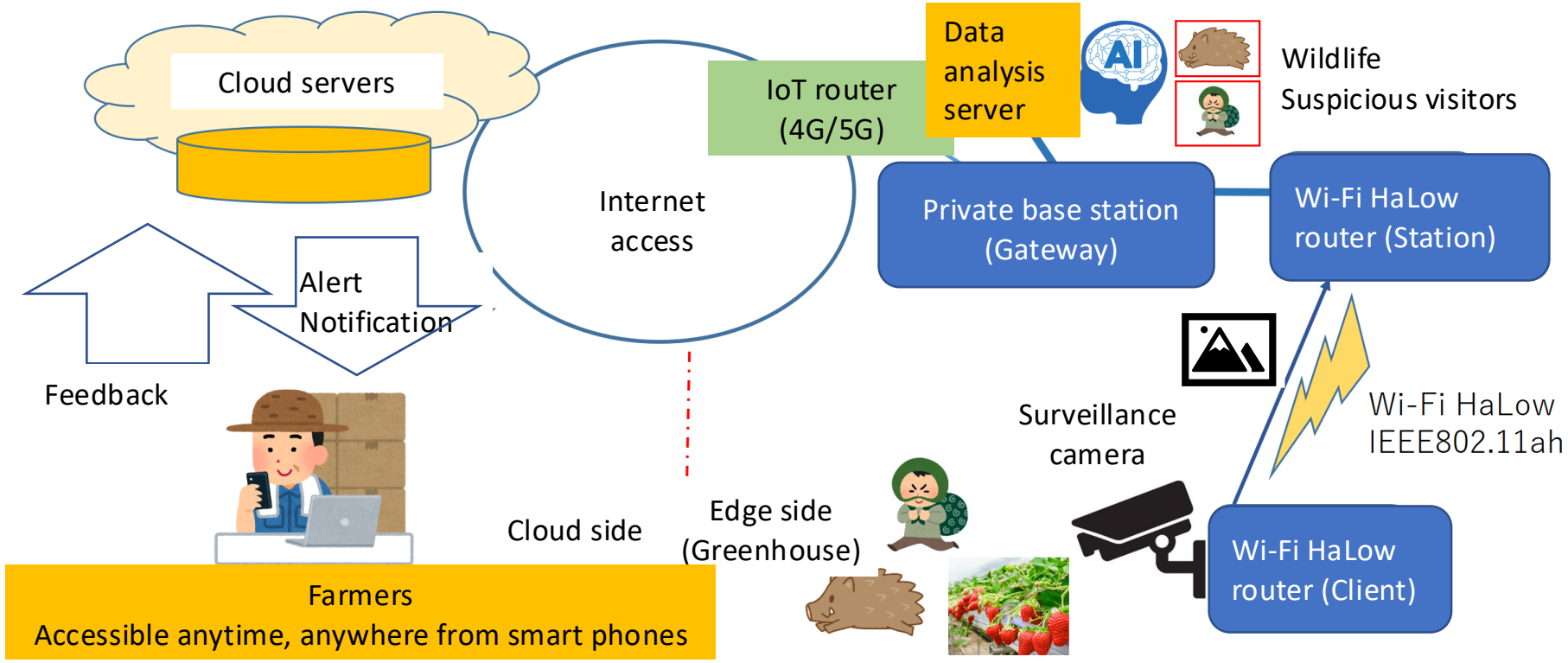
Strawberry (automatic) harvesting robot

- The robot can automatically determine the strawberry's maturity using visual analysis AI and its actions based on the results.
- In Japan, the 6-GHz frequency band has been newly assigned for Wi-Fi 6E. There is less interference in this spectrum because it is rarely used.
- Robot controls require strict throughput and latency. Thus, mmWaves can potentially solve the fundamental spectrum-hungry issue.

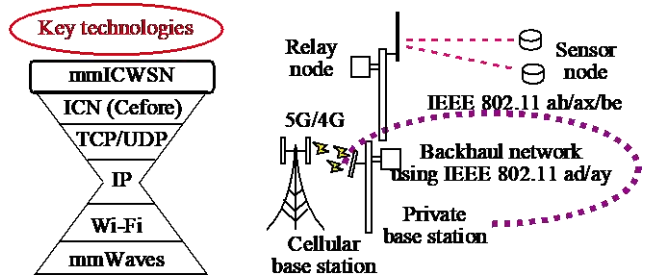


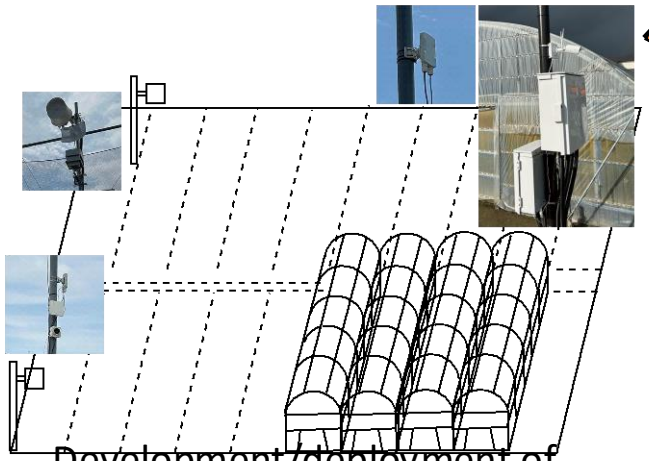
Security management and pest prevention system

- The system collects and analyzes the visual data from the surveillance camera. If the image analysis AI on the edge computer detects suspicious visitors and harmful wildlife, it sends alerts to the farmer.
- The farmers can remotely obtain the strawberry (growth) conditions, and they adjust the irrigation and fertilizer as needed.
- The system can only send low-resolution visual data due to the narrow HaLow spectrum and restrictions under Japan's radio regulations.
  If it is replaced with mmICWSN, the network environment can be improved.

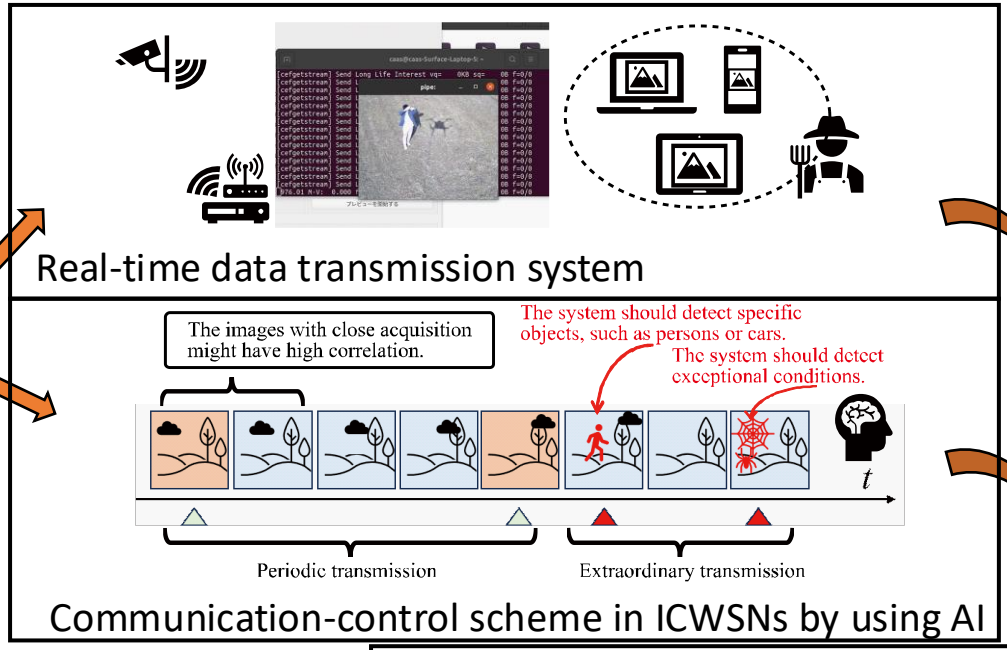


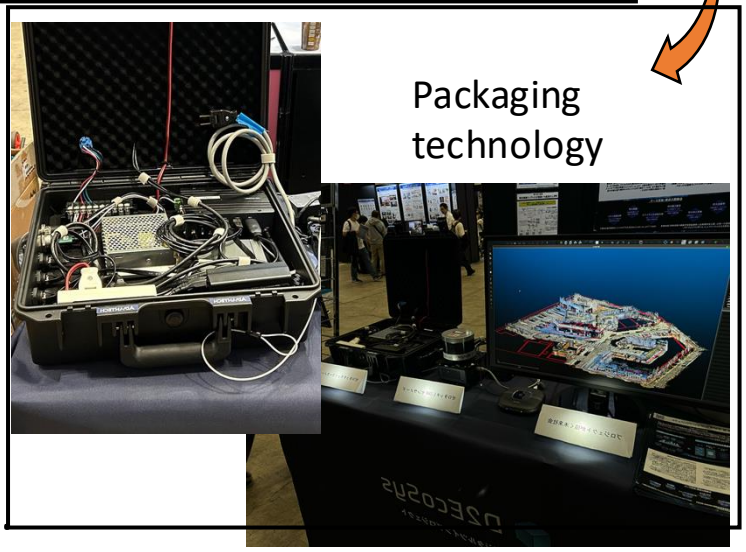
ICWSN platform deployment for smart agriculture





Development/deployment of mmICWSN platform in the farm



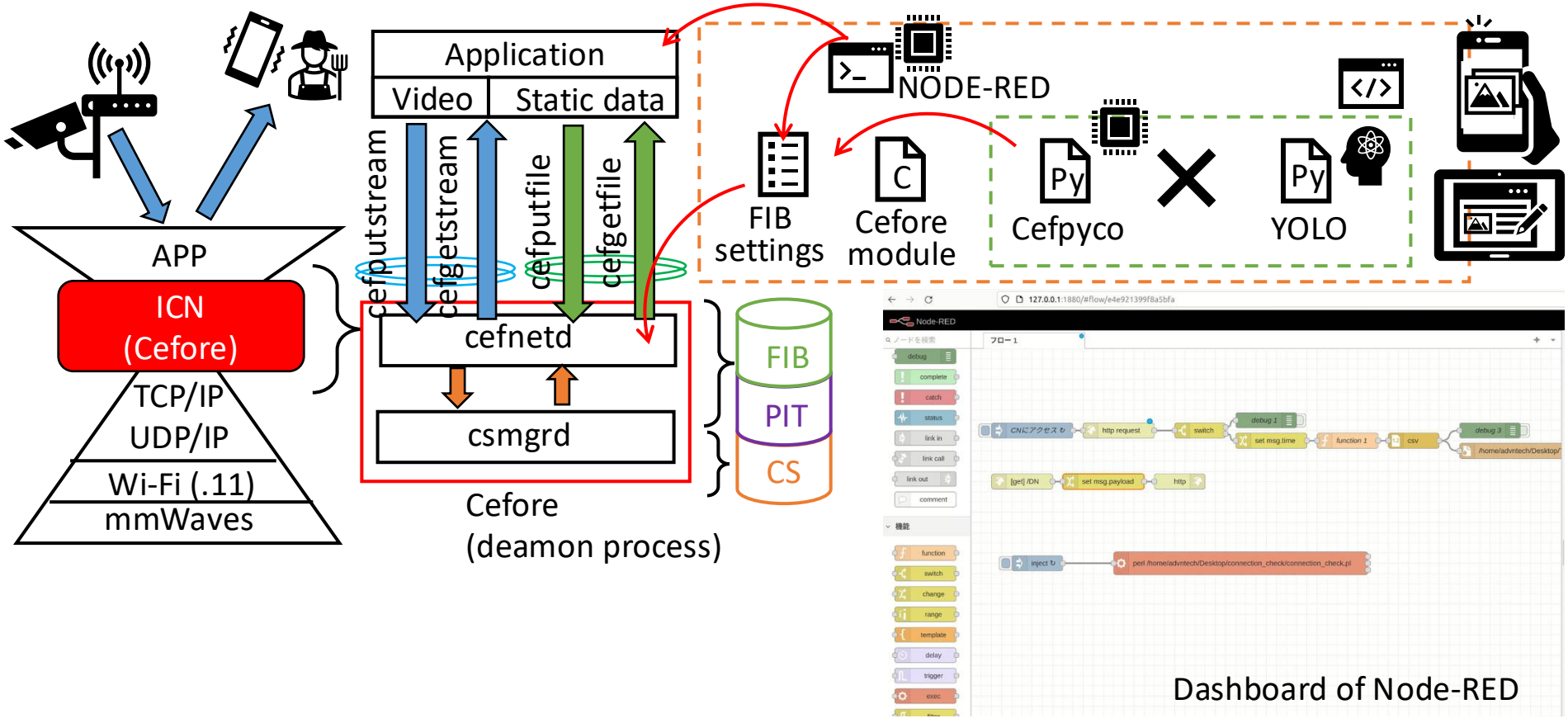


- Development/deployment of mmICWSN.
- Real-time data transmission scheme.
- ICN control using AI based on visual data.
- Packaging technology for horizontal development

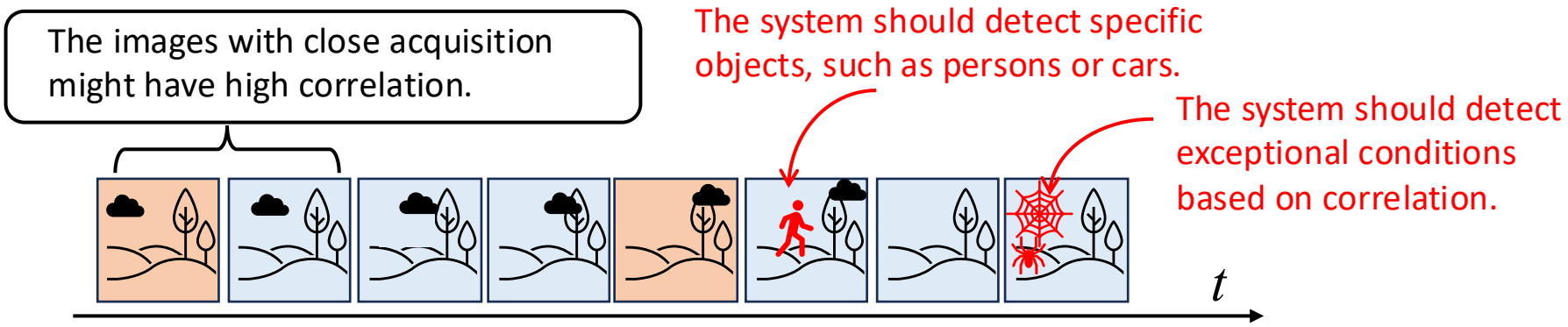
[10] S. Mori, “Concept of ecosystem for smart agriculture: Millimeter-wave information-centric wireless visual sensor network,” *Proc. IARIA Congress 2025*, pp. 33–37, Venice, Italy, July 2025.

Real-time data transmission system

- The proposed mmICWSN will use Cefore for the middleware of the ICN platform.
  - To reduce implementation costs, we will implement it by combining the Python-based Cefpyco provided by Cefore and Python-based AI.
  - For simplified deployment, we will implement a control app using NODE-RED.
  - We will provide the service as an app for smartphones and tablets.



Communication-control scheme in ICWSNs by using AI



- Challenges to be overcome in the mmICWSN framework and networking
  - Even if we use WLANs, and WLAN can use different frequency bands for various coverages; nevertheless, bottleneck sections will remain.
  - It is difficult to transmit all video and image data; we remove the barriers.
- General characteristic of visual data (videos/images)
  - The pixels around a particular pixel are often similar.
  - Variations and differences between pixels depend on time and location.

- Since the visual data does not change significantly over short intervals, the data can be downsampled (compressed).
- The transmission interval can also be adjusted using any event as a trigger, i.e., if the AI detects any object, the proposed scheme can be sent as an exception.

Conclusion

- We presented an overview of the two research projects.
- We provided a plan for a new smart agriculture project with industry-academia-government collaboration.

Preparation status

- We have negotiated the use of a local farm for deployment and demonstration.
- We are conducting preliminary studies and prototype implementations (ongoing).

Contribution for future wireless networks

- MmICWSN can effectively use radio spectrums, and it can also reduce energy consumption as a side effect, making it greener.

Future work

- We will acquire funding to launch the smart-agriculture project.
- We consider that the ICWSN platform can support on-demand and real-time data transmissions with mixing various (QoS) demands.
- We plan to expand horizontally into other fields, such as Industrial IoT.

Thank you for your attention.

This work was partly supported by JSPS KAKENHI Grant Number 25K15104.