IARIA ICN 2024
(Barcelona, Spain)

(Keynote) Information-centric Wireless Networking

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Biography

Shintaro Mori received his B.S., M.S., and Ph.D. degrees from Kagawa University in 2007, 2009, and 2014, respectively. Since April 2014, he has been with the Department of Electronics Engineering and Computer Science, Faculty of Engineering, Fukuoka University, Japan, where he is currently an assistant professor. His research interests include cross-layer design, wireless sensor networks, and information-centric networks. He is a member of IEEE, ACM, IEICE, ISSJ, and RISP.

- Topics of research interest:
  - Wireless information-centric networking (WICN)
  - Information-centric wireless sensor network (ICWSN)
  - Cooperative communications and blockchain for green and secure ICWSNs
  - mmWave-band unmanned aerial vehicle-assisted ICWSNs
  - Cross-layer design for wireless communication and network system

- For more information, please see my website:
  - https://www.cross-layer.com/

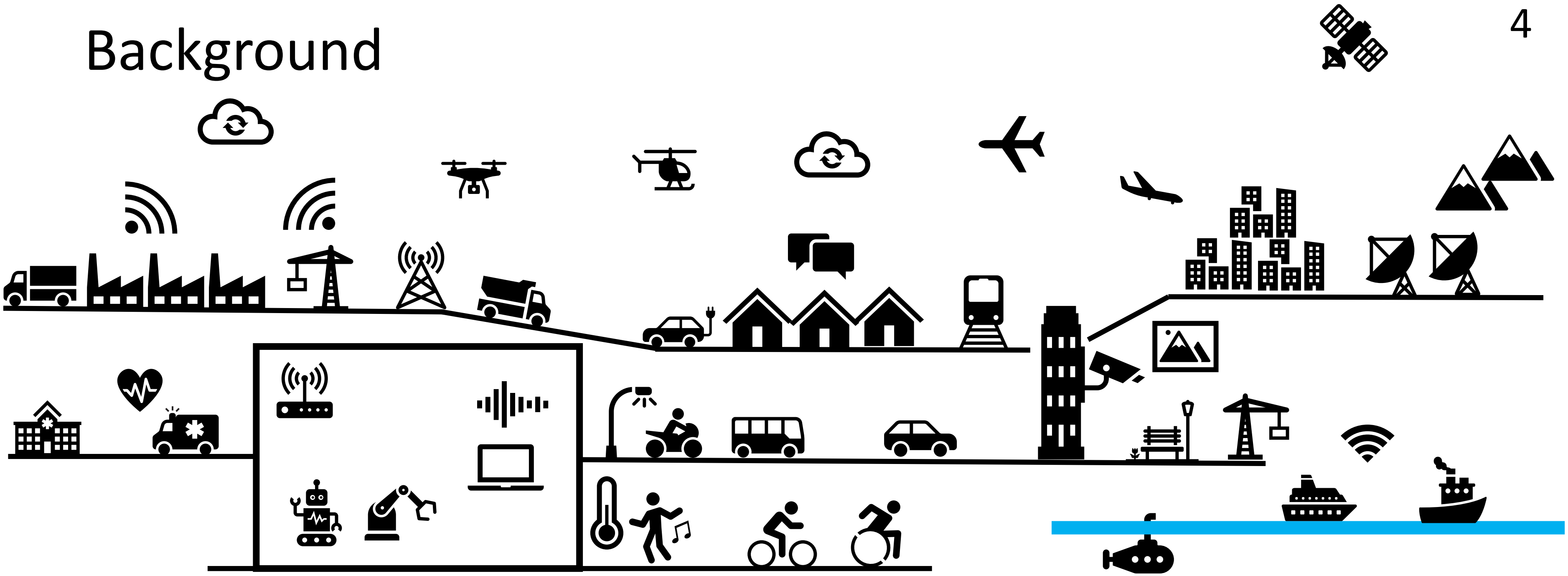
Agenda

- Introduction
  - Information-centric networking (ICN)
  - Information-centric wireless sensor networks (ICWSNs)
- Research activities
  - Effective caching scheme for ICWSNs
  - Secure caching scheme with blockchain (BC) for ICWSN
  - Medium access control (MAC) and physical (PHY) design for ICWSNs

    Question: What services will you use ICWSN for?
    Answer: We apply it to various services underpinning smart cities.

  - Application services for ICWSNs
    - ICWSNs for disaster-resilient smart cities
    - Green ICWSNs for sustainable smart cities
  - Ecosystem development as a smart-city-as-a-service framework
- Conclusions

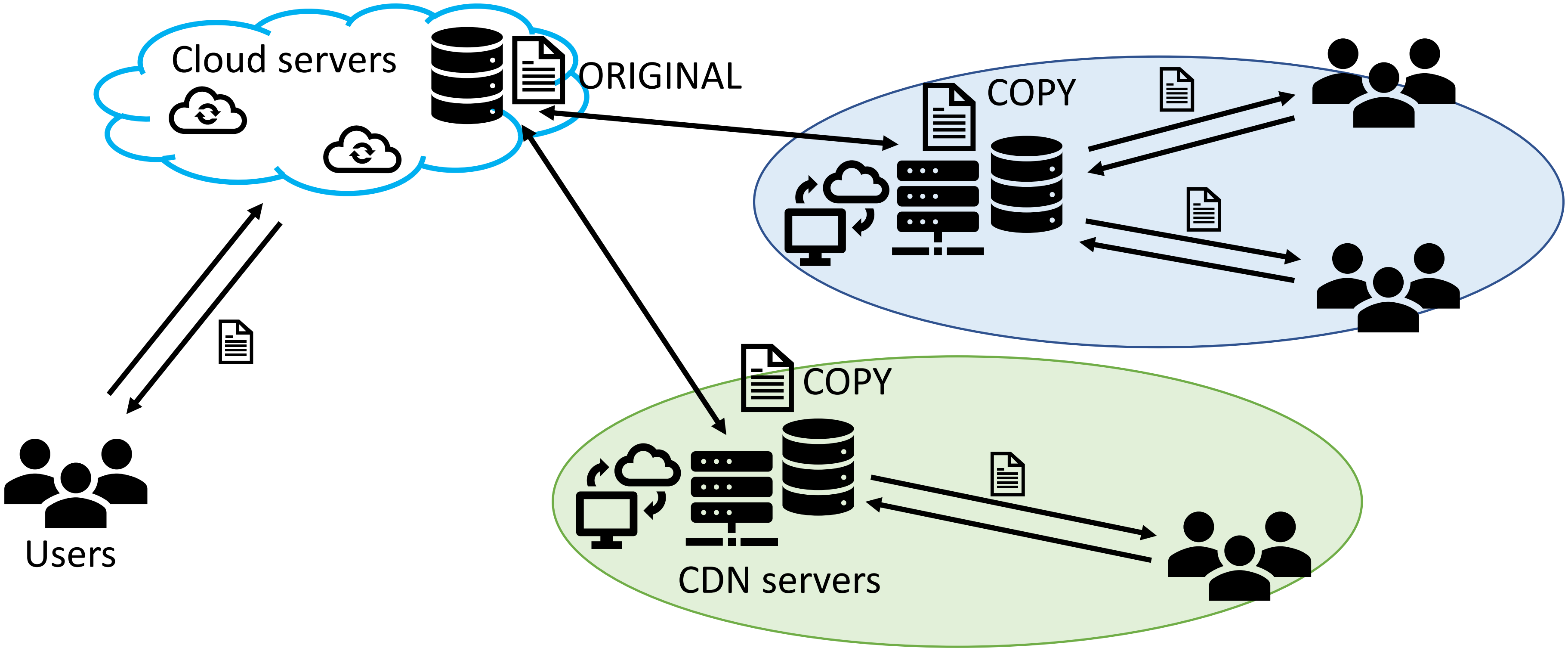
Background



- Emerging technologies, such as Internet of Things (IoT), metaverse, and artificial intelligence, enable crowd sensing in central city areas to be smarter [1].
- Using massive amounts of valuable information they produce, problems with urbanization and social needs can be resolved (through collaboration between academics, industry, and government in some cases).
- This makes cities greener, safer, and more hospitable for residents.

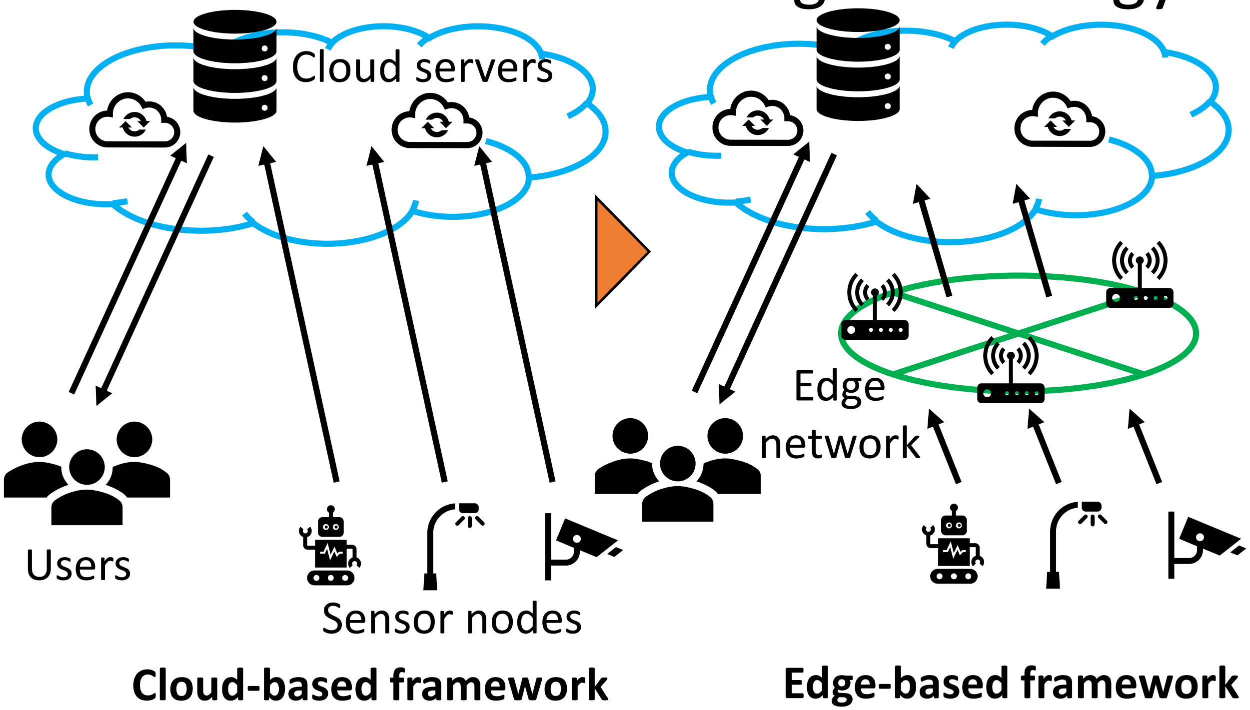
[1] P. Mishra, et al., “6G-IoT framework for sustainable smart city: Vision and challenges,” *IEEE Consumer Elect. Mag.*, pp. 1–8, 2023.

Evolution of networking technology



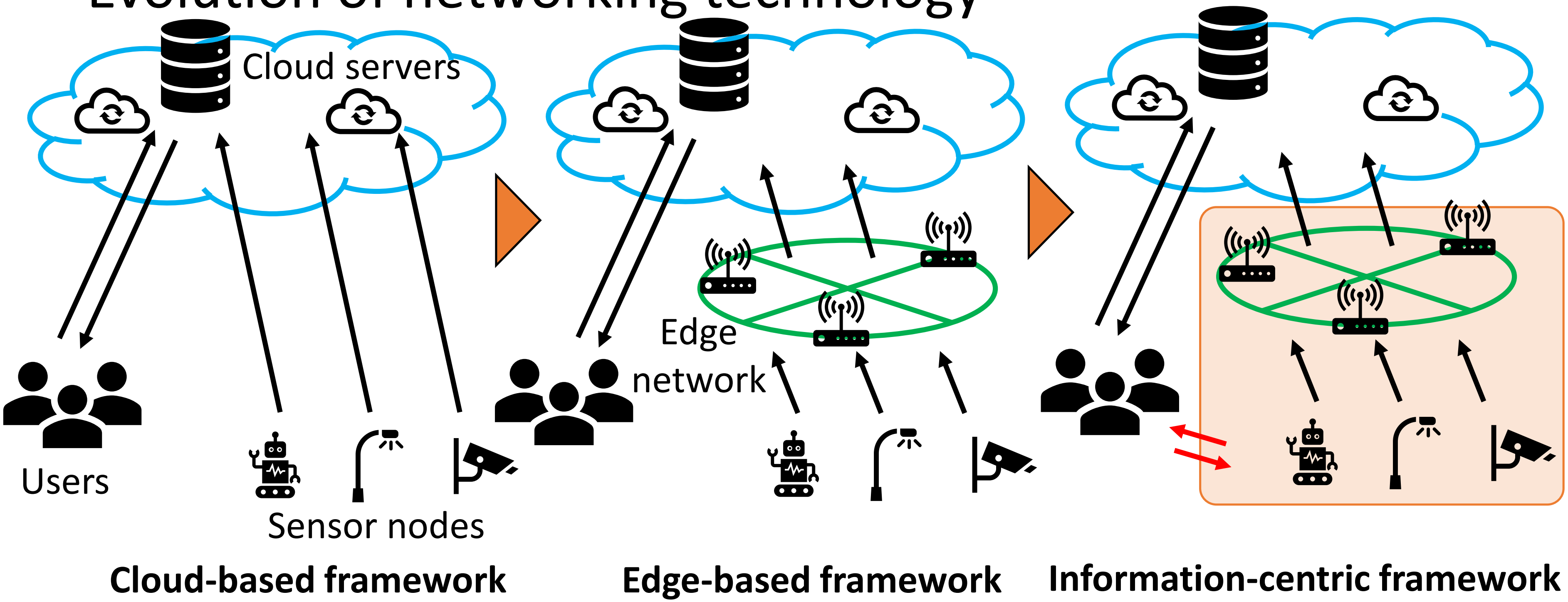
- In the current network system, data are gathered and stored on the cloud servers, and the users find and obtain them from the central locations.
  - With the growth of data consumers, network bandwidth will be too tight.
- The content delivery network (CDN) technique is widely used to improve network congestion, especially in the area around the central servers.
  - CDN servers are distributed to specially deliver the cached (copied) data.
  - Users can obtain data from the geographically closest servers.

Evolution of networking technology



- Legacy cloud-based IoT framework provides application services across mutual regions, which manage the application images and data.
- In some IoT services, the primary functionalities shift from cloud to edge networks to improve the latency and quality of (wireless) networks.
- The fusion of cloud and edge computing will enhance future IoT services.
  - The technical issues remain regarding data processing capacity, transfer efficiency, etc.
  - These problems originated from cloud dependency.

Evolution of networking technology



- The research community currently explores a new IoT framework for effective content collection and distribution [2].
- Information-centric networking (ICN) [3] can be a promising solution.
  - The data are given unique and location-free names and stored everywhere in the network; thereby, the users can fetch them directly and effectively.

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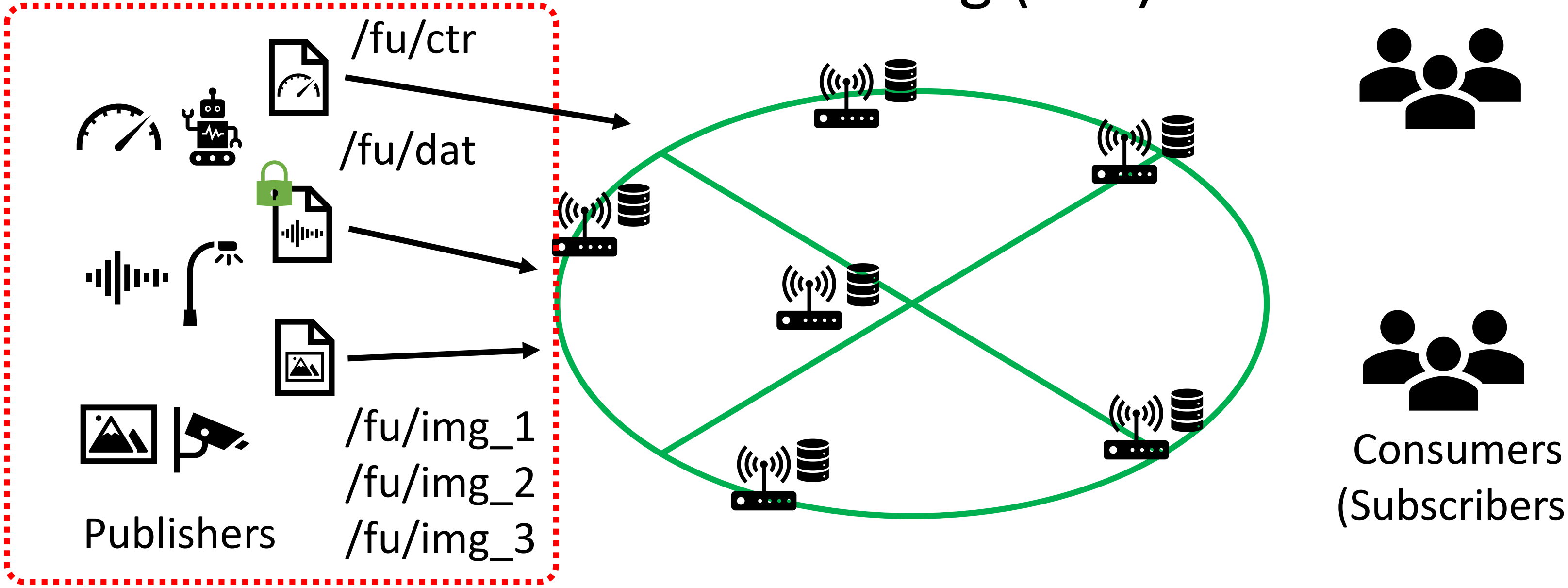
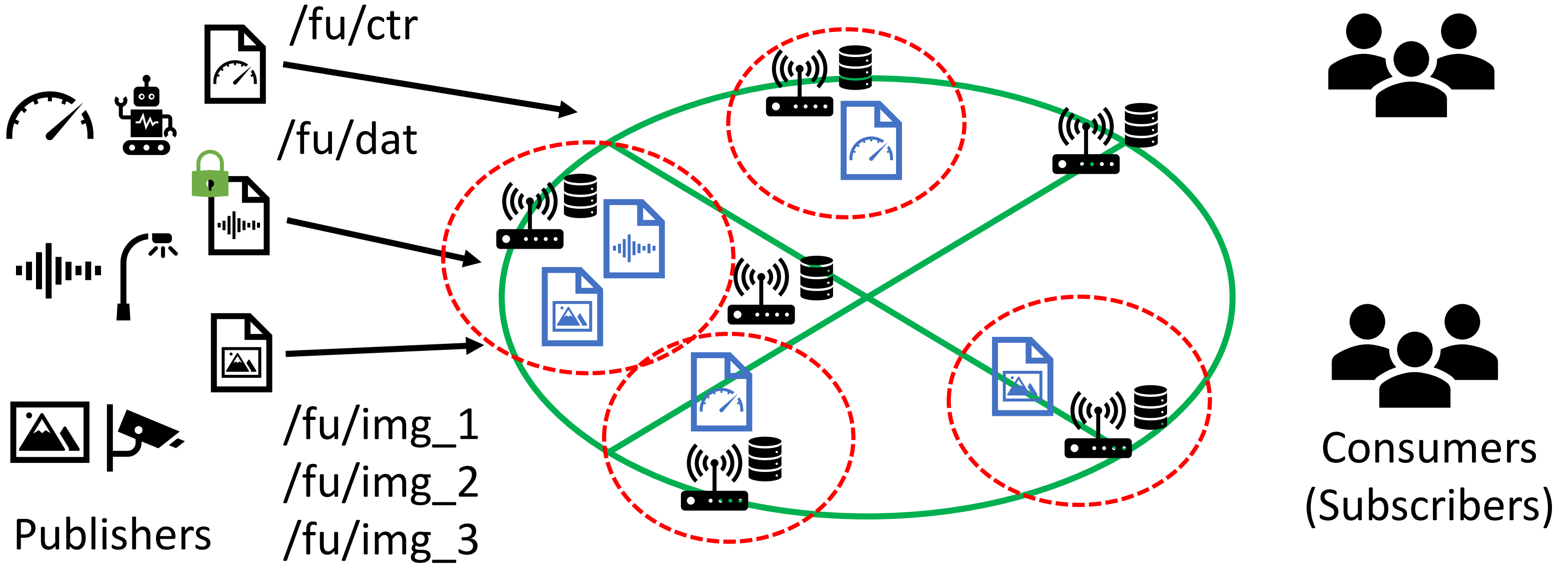
[2] M. Amadeo et al., "ICN for the IoT: Challenges and opportunities," *IEEE Network*, **30**, 2, pp. 92–100, 2016.
[3] B. Ahlgren, et al., "A survey of ICN," *IEEE Commun. Mag.*, **50**, 7, pp. 26–36, July 2012.

Information-centric networking (ICN)



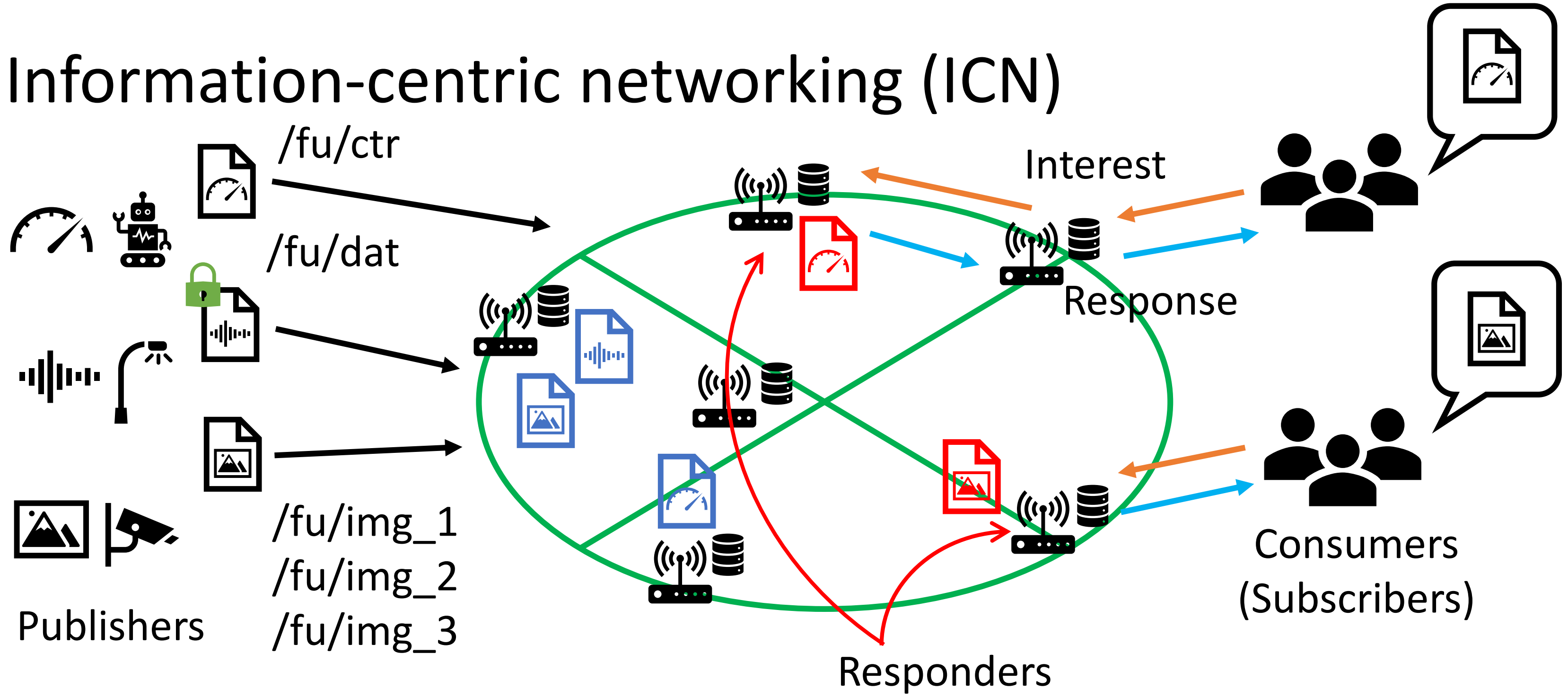
- ICN is a data-oriented network protocol that focuses on content delivery.
  - The search engines (or domain name systems) reply with the IP address for the keyword, and the users obtain the data based on the address.
  - Peer-to-peer (P2P) networks find the node with the data, and the user directly communicates with the node based on the address.
- ICN deals with the data as a named data object (NDO) for every piece of information, e.g., sensing data, images, videos, and other contents.
  - NDOs are detached from location, application type, and protocols.
  - The ICN protocol-tier security can be resolved for every NDO.
  - As an ICN option, a large-data-size NDO can be divided into several chunks.

Information-centric networking (ICN)



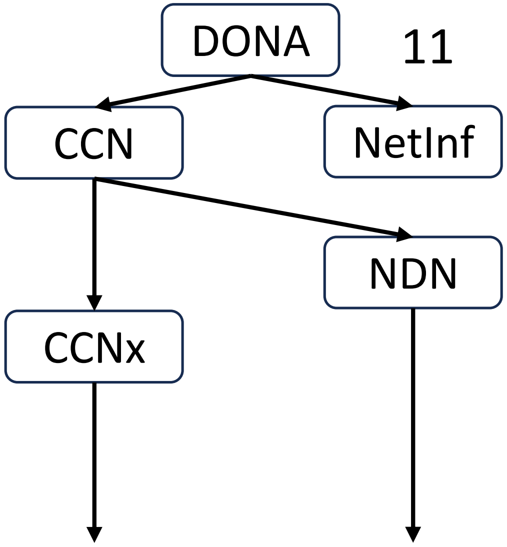
- Specific ICN features:
  - The data-transfer method is based on a multi-cast and multi-path network.
  - An in-network caching scheme is equipped; anyone can provide the data as long as they have it anytime and anywhere.
  - End-to-end connections should not be required, simplifying management, such as handover; the publishers and consumers can be decoupled.
- ICNs' advantages:
  - Mobile publishers just submit the data to the network, and mobile consumers simply post the request for data retrieval to the network.
  - The smaller overhead for data exchange improves network congestion and latency, which can reduce wireless spectrum and energy consumption.

Information-centric networking (ICN)



- ICNs mainly use two types of packets: an interest (find) and a response.
  1. The consumer posts the interest packet with clues to find the data.
  2. When a node receives an interest packet, if the node holds the data, the node is assigned as a responder; otherwise, the interest packet is further forwarded.
  3. The responder replies with the response packet that encapsulates the data.
  4. The consumer has obtained the data.
- There is no need to distinguish between original or copy.

History of ICN platform [4]



- Data oriented network architecture (DONA)
  - The naming rule is replaced with hierarchical URLs, but it is maintained IP-addressing resolution.
  - DONA is overlayed the map between (flat) names and their corresponding data.
- Named data networking (NDN)
  - NDN is one of the famous ICN platform.
- CCN/CCNx
  - Three databases are used: forwarding information base (FIB), pending interest table (PIT), and content store (CS).
  - Interest packets can be transferred to the next node based on FIB.
    - The outgoing interfaces for each known naming prefix are stored.
  - Response packets can be sent back based on PIT.
    - The trace (routing) information is recorded among intermediate nodes.
    - These traversal records are removed while reverse-forwarding the data.
  - Cached data are managed using CS.

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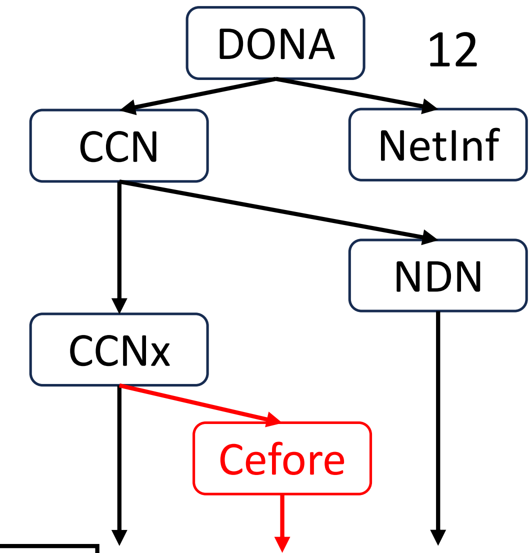
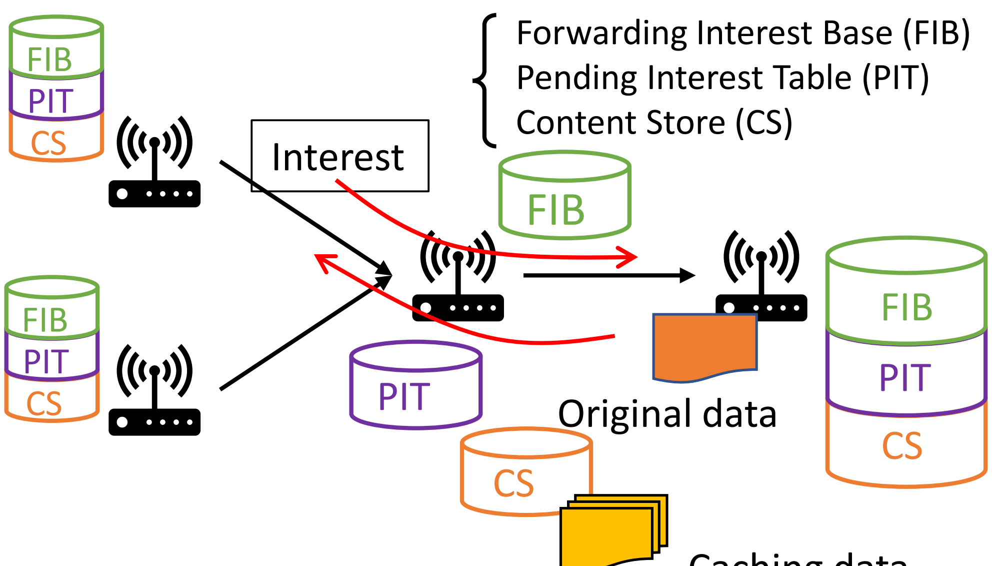
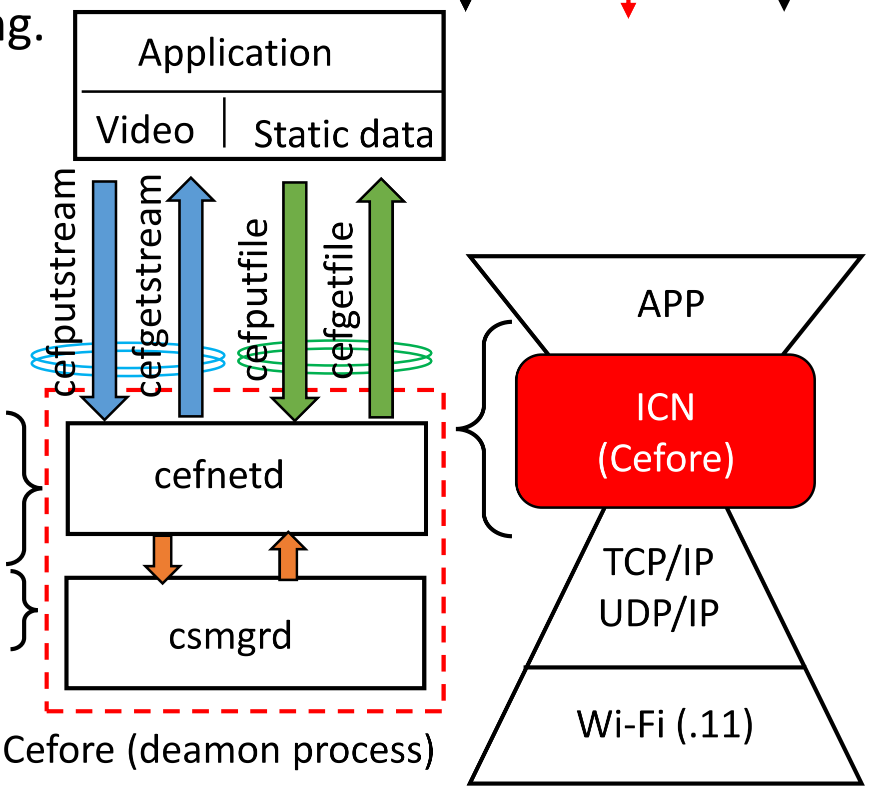
[4] G. Xylomenos et al., "A survey of ICN research," *IEEE Commun. Surv.&Tut.*, **16**, 2, pp. 1024–1049, 2014.

ICN platform: Cefore [5]

- We select Cefore as an ICN platform.
  - Static data:
    - "cefputfile" is used to commit a data.
    - "cefgetfile" is used to acquire the data.
  - Video streaming:
    - "cefputstream" delivers video streaming.
    - "cefgetstream" receives the video.







Caching data is kept in cache memory for 300 seconds, and the old data is deleted according to the FIFO rule.

[5] Cefore, https://cefore.net/ (retrieved: May 2024)

ICN meets WSNs

- One of the essential elements in IoT frameworks is the wireless sensor network (WSN) because it provides useful information anywhere and anytime.
- The WSNs face several problems, especially in high dynamic network topology under autonomous-distributed environments.

▼

- Combining ICN and WSN is suitable because they are similar perspectives.
- Information-centric wireless sensor networks (ICWSNs) [6] can be a breakthrough to resolve the chronic problems of WSNs for IoT.
- Advantages of ICWSNs:
  - Since ICWSN-based data retrieval is location-independent, the system can work in dynamic wireless network environments, including node movement and suddenly unavailable.
  - Massive HTTP-based requests cause considerable protocol overhead, whereas ICWSN can improve them.

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[6] B. S. Kim, et al., "Guest editorial special issue on ICWSN for IoT," *IEEE IoT J.*, **9**, 2, pp. 844–845, 2022.

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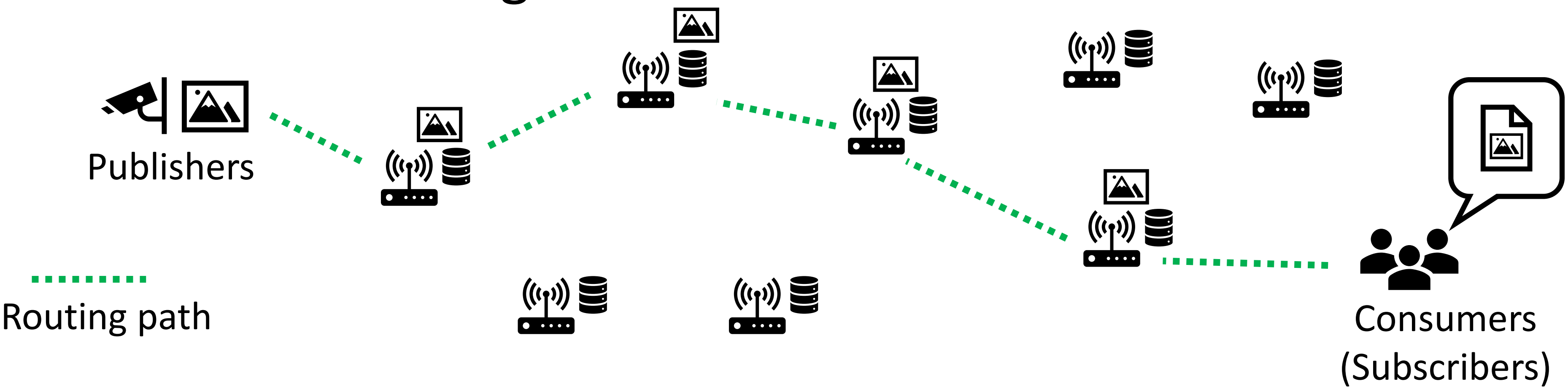
Effective caching scheme for ICWSNs



- In ICWSN, the in-network caching scheme can be classified into on-path and off-path caching [7].
  - On-path caching: The data are cached at the nodes along the routing paths.
  - Off-path caching: The data are cached at any nodes without routing paths.
- In our studies [8][9], we focus on the off-path caching method, and we proposed an effective caching scheme for ICWSNs.

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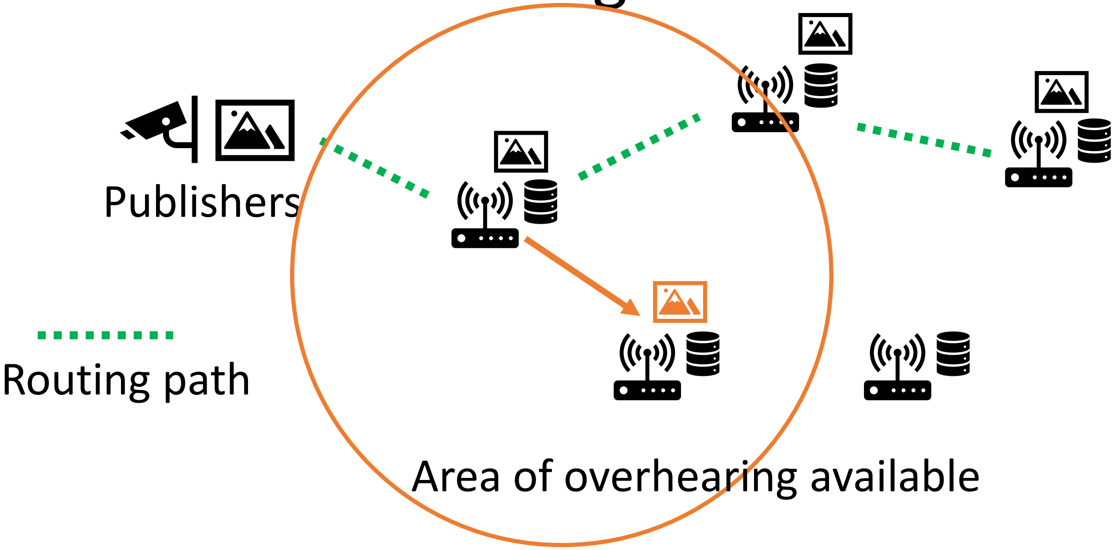
[7] M. Dräxler, et al., "Efficiency of on-path and off-path caching strategies in ICNs," *Proc. IEEE GreenCom*, 2012.

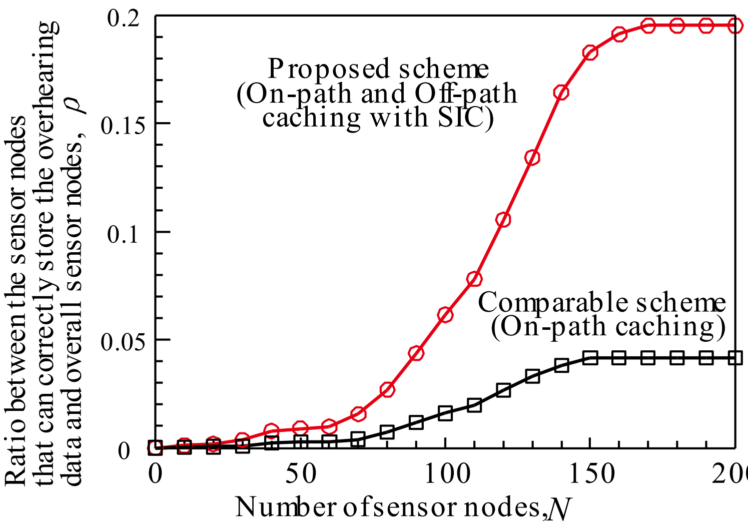
[8] S. Mori, "A study on off-path caching scheme by using SIC for ICWSN," *Proc. IARIA ICN*, 2017.

[9] S. Mori, "Cross-layer design for caching scheme by using SIC in ICN-based WSN," *Int. J. Adv. in Netw. & Serv.*, **10**, no. 3&4, pp. 142–151, Dec. 2017.

Effective caching scheme for ICWSN



■ Results



- Overhearing in wireless communications: When nodes wirelessly transmit data, their neighbors can receive the data due to the feature of radio's airdrops.
- The proposed scheme [8][9] uses this phenomenon for effective off-path caching.
  - Although the system consumes additional energy through overhearing processing, it is smaller than wireless communications.
  - The successive interference cancellation technique is also used; the strongest signal (the most critical influence on a neighbor interference) among the received signals can be subtracted if it has been decoded.

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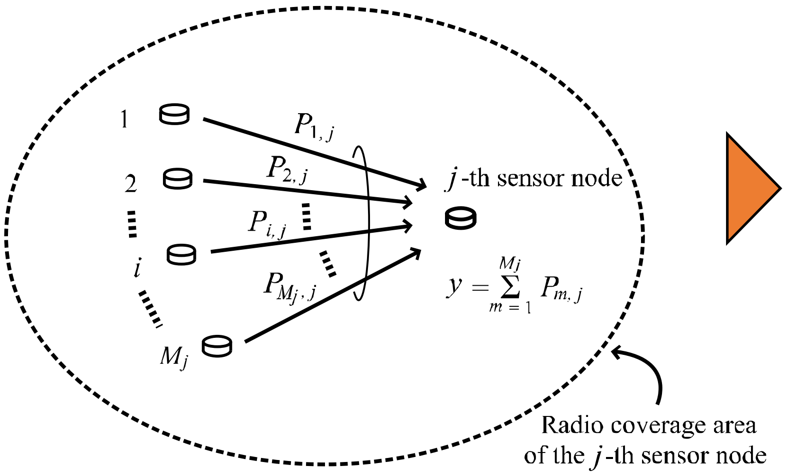
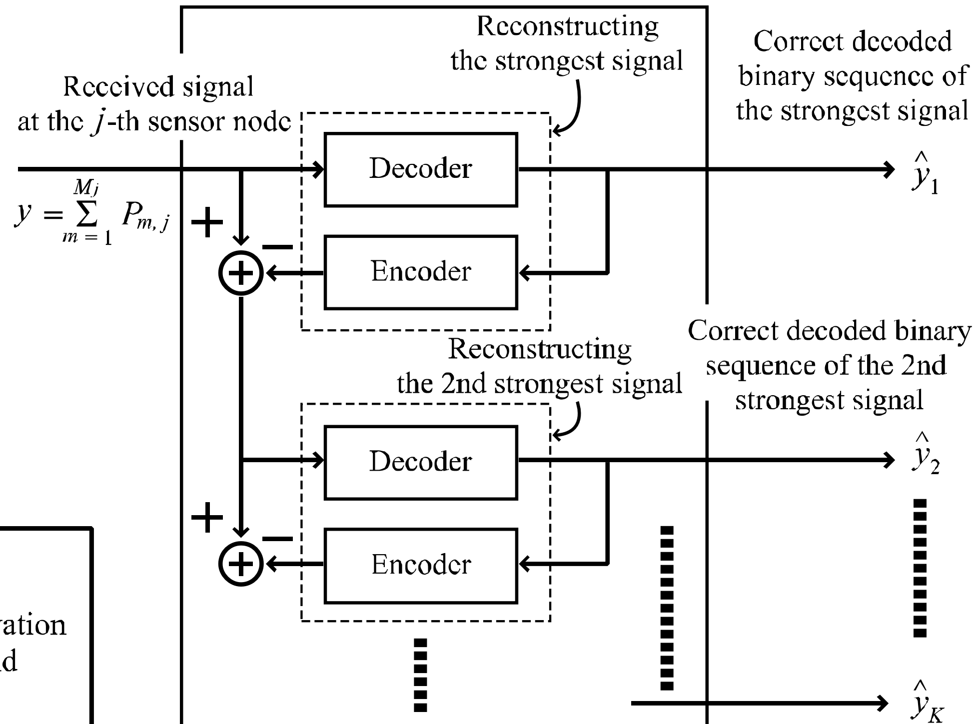
[8] S. Mori, "A study on off-path caching scheme by using SIC for ICWSN," *Proc. IARIA ICN*, 2017.

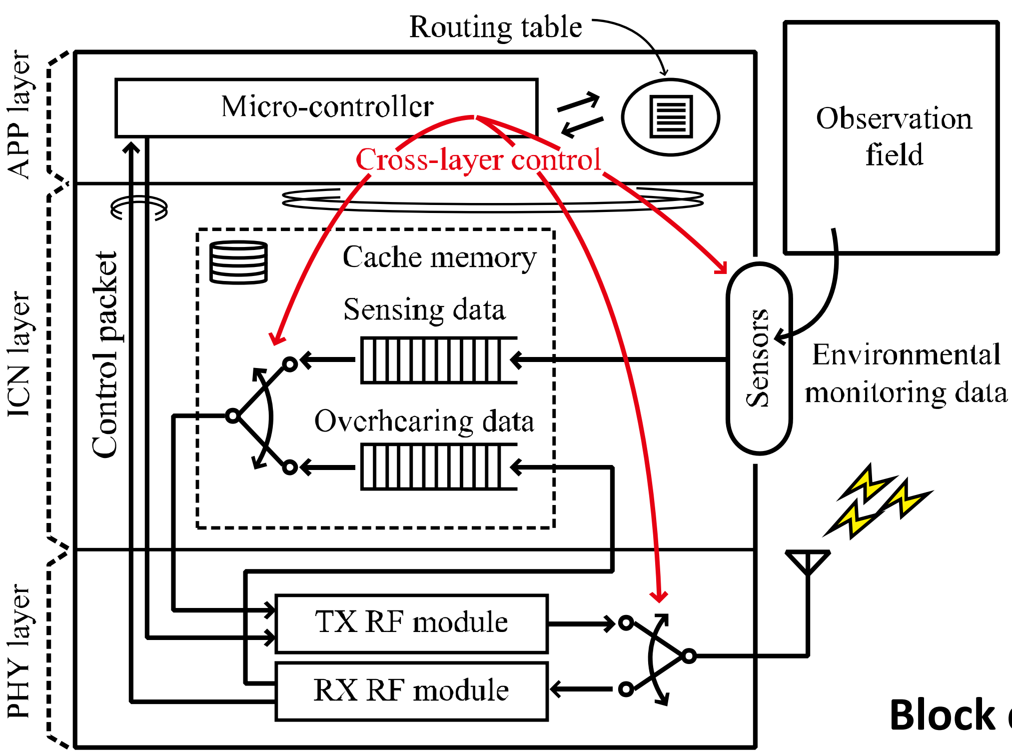
[9] S. Mori, "Cross-layer design for caching scheme by using SIC in ICWSN," *Int. J. Adv. Netw. & Serv.*, **10**, 3&4, pp. 142–151, 2017.

Effective caching scheme for ICWSN





Overview of the proposed scheme with SIC technique



Block diagram of the proposed scheme

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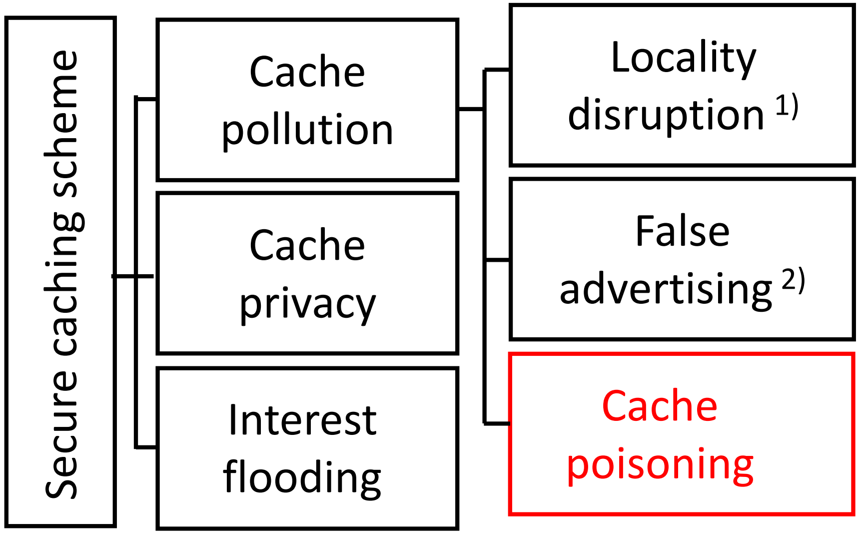
Secure caching scheme with blockchain for ICWSN

- The caching scheme should be actively worked in ICWSNs for effective data distribution and reducing network congestion.
  - Regardless of on-path or off-path caching methods, the cached data should be scattered as much as possible.
- At the same time, in many cases, the ICWSN must deal with the secured data.

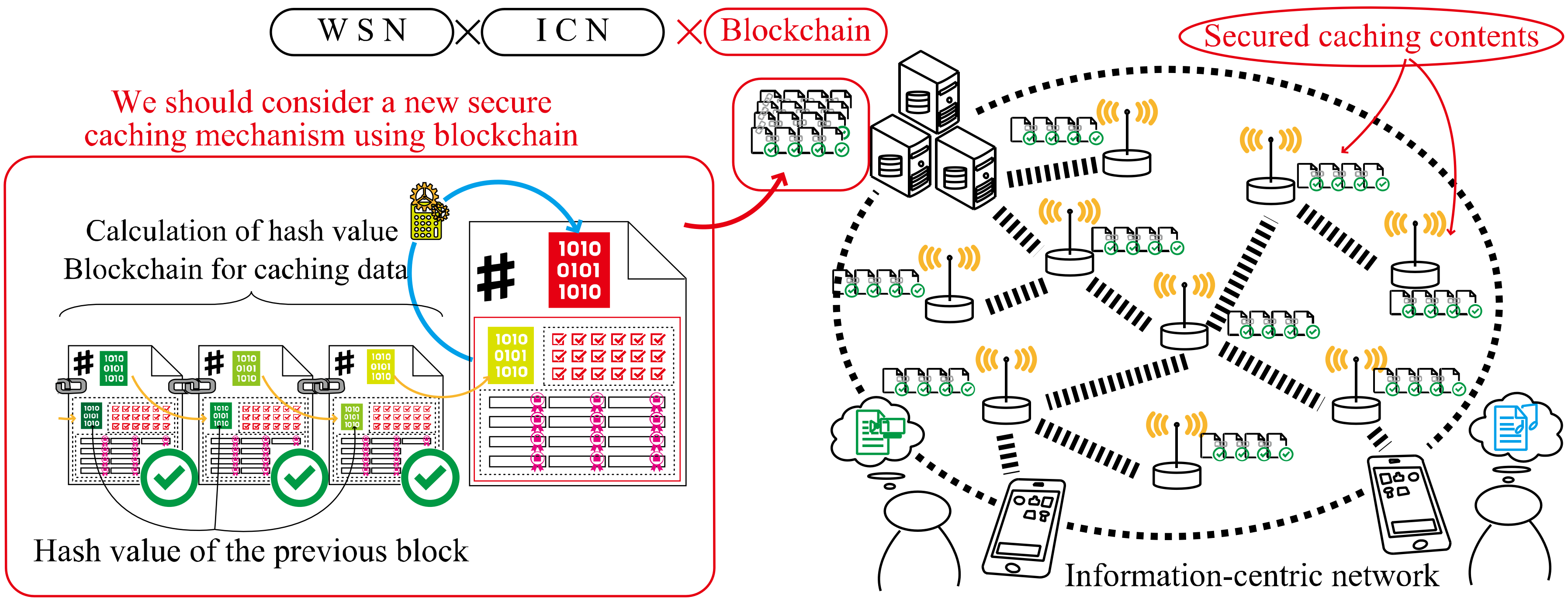
- In our studies [10][11][12], we investigated a secure caching scheme for ICWSNs.
  - The proposed scheme achieves a decentralized management and secured handling of the caching data.



[1] Disguising unpopular data as popular.
[2] Spreading malicious/corrupted data to neighboring nodes.

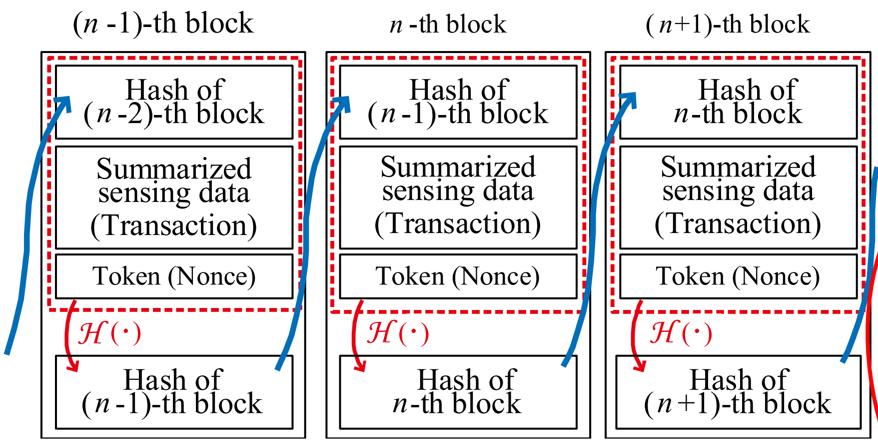
[10] S. Mori, "Fundamental analysis for blockchain-based secured caching scheme for ICN-based WSN," *Proc. RISP NCSP,* 2018.
[11] S. Mori, "Secured caching scheme by using blockchain for ICN-based WSN," *J. Signal Process.*, **22**, 3, pp. 97–108, 2018.
[12] S. Mori, "(Invited) Secure and effective caching scheme using blockchain for ICWSNs," *Proc. APSCIT,* 2019.

Secure caching scheme with blockchain for ICWSN



- We use blockchain (BC) to protect cache pollutions.
  - Once the data is verified and registered in the BC-based ledger, it can be trustworthy without reconfirming when users retrieve it.
- Reasons that we select the BC:
  - ICN, WSN, and BC work in an autonomous and decentralized environment.
  - BC can be constructed among anonymous nodes, this is reasonable for heterogenous WSNs, and BC's verification process is simple and common.

Secure caching scheme with blockchain for ICWSN



$$h_{n|\kappa} = \mathcal{H}(h_{n-1|\kappa} \oplus \overline{\mathbb{D}}_n \oplus I_n) \quad (1)$$

$$I_n \neq \mathcal{H}^{-1}(h_{n-1|\kappa} \oplus \overline{\mathbb{D}}_n \oplus h_{n|\kappa}) \quad (2)$$

Sensing data: $\overline{\mathbb{D}}_n$ Nonce: I_n

Hash value: $h_{n-1|\kappa}$ Hash function: $\mathcal{H}(\cdot)$

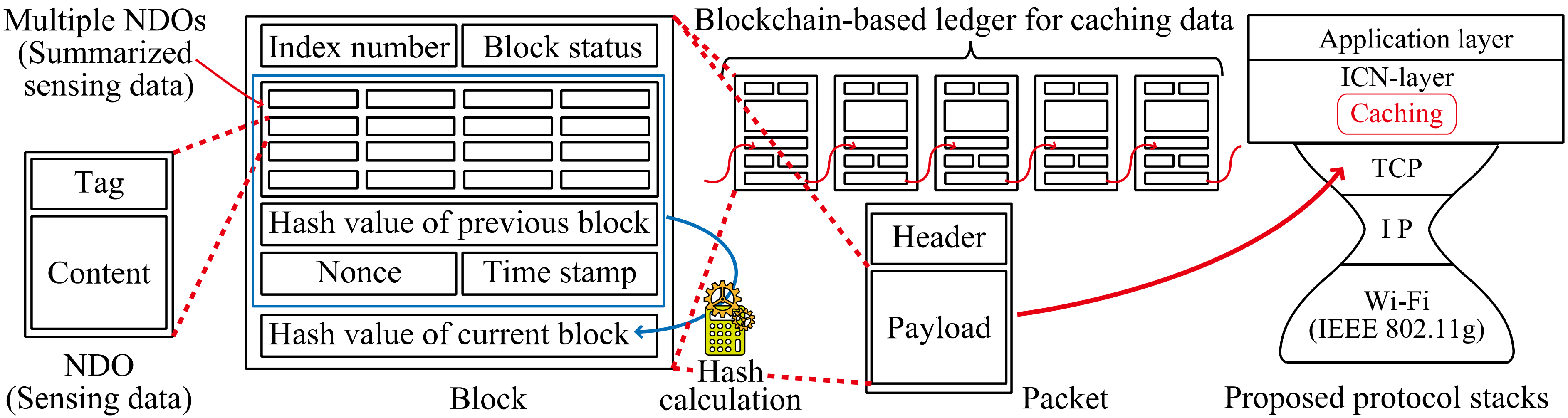
Hash value of the n-th block

0000 0000 0000 1101 0100 1011 0010 1011

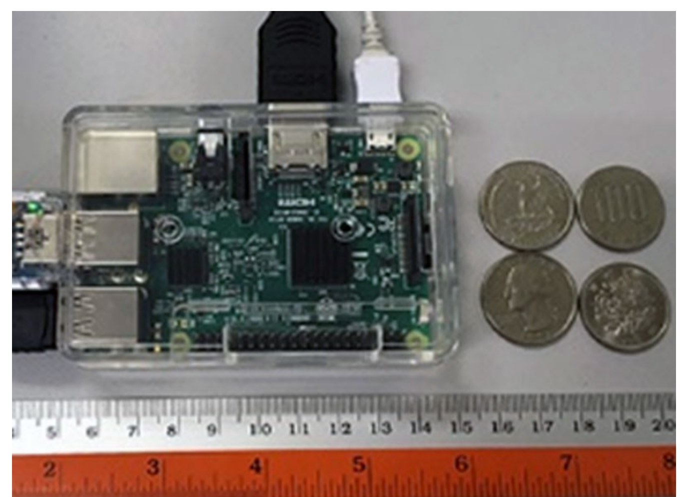
$h_{n|\kappa}$ must satisfy the condition that the bit sequenct is followed by a long string of zeros with κ bits from the MSB

- Miner nodes calculate the hash value based on (1) with brute-force competition while changing nonce, a temporal random value.
- The BC's hash value must be satisfied with zero from the most significant bit (MSB) to the κ-th bit.
- The guarantee of the BC's robustness comes from the difficulty of calculating using an inverse hash function in (2), compared to (1).
- The parameter (difficulty), κ, is calibrated depending on the network nodes in the mining-based verification transaction.

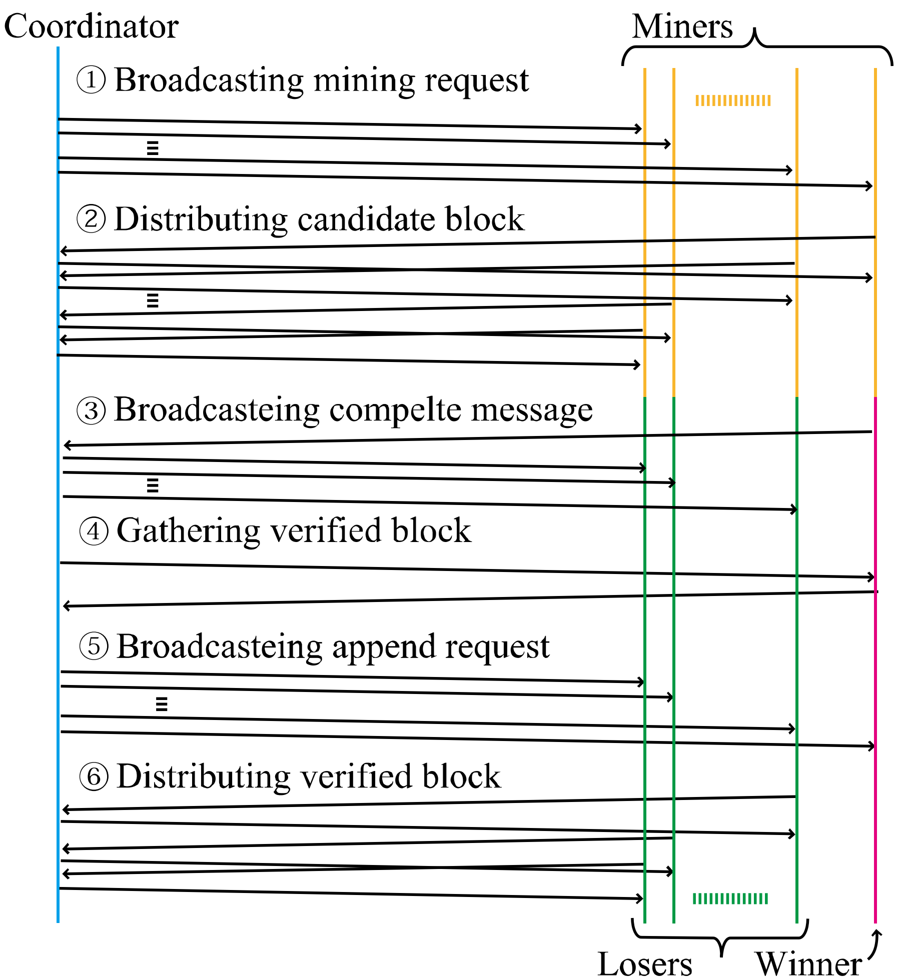
Secure caching scheme with blockchain for ICWSN



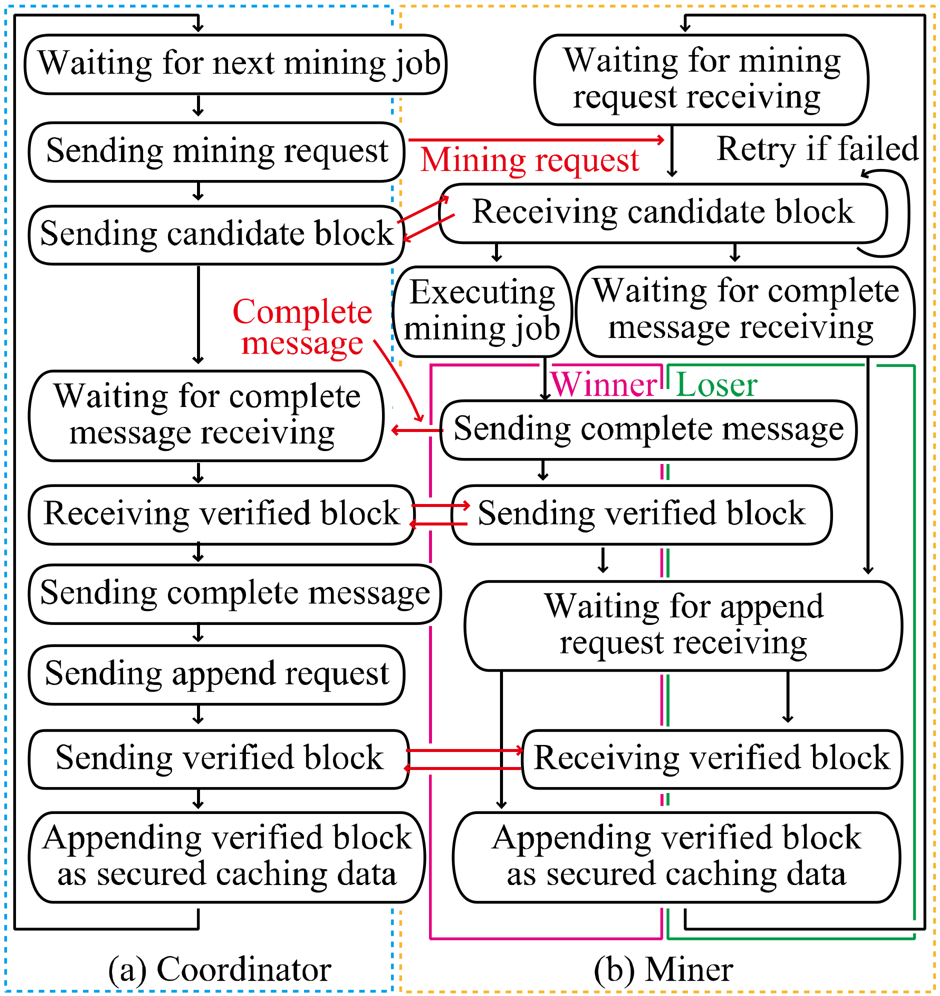
- In our studies [10][11][12], we developed a BC-based secure caching protocol.
- Definition of the data structure:
  - NDO is equivalent to sensing data.
  - Block is a data unit in the BC, including NDOs, index, status, and hash value.
- Control messages: Mining request, complete, and append request.
- The testbed was implemented using Raspberry Pi 3 device with the Raspbian kernel version 4.9.



Secure caching scheme with blockchain for ICWSN



Proposed verification procedure



Transitional state of coordinator and miner in case of control message receiving

Secure caching scheme with blockchain for ICWSN

■ Testbed implementation

- We select the general-purpose MD5 and SHA-1 algorithms in the hash function.
- The simulation program was implemented using C++ with the CLX library.

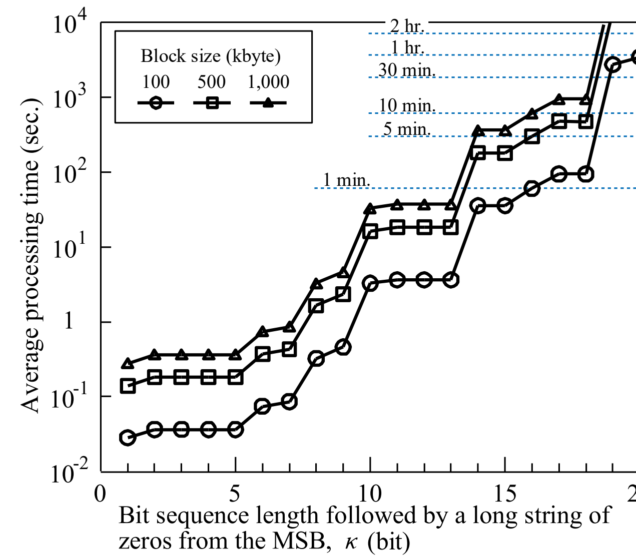
■ Experiment environment

- Results shows the κ vs. average processing time.
  - Difficulty, κ, was set as 1–20.
  - Block size was set as 100, 500, and 1,000 kbytes.

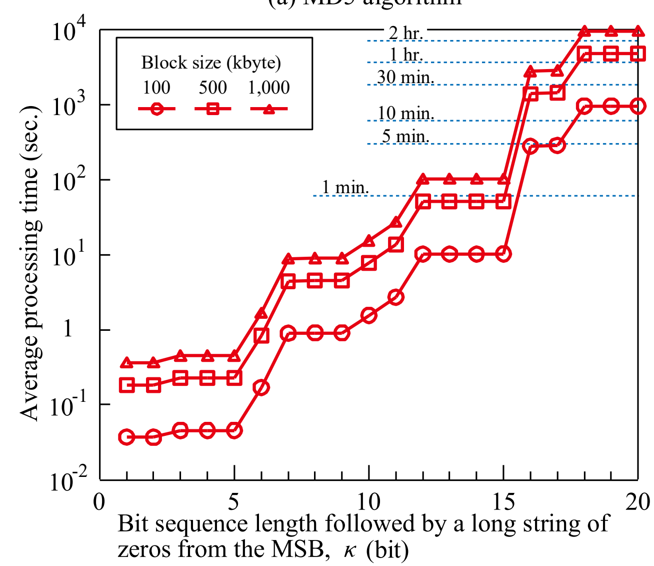
Example of difficulty κ settings for secure ICWSN

Block size (kbyte)	MD5		SHA-1	
	1 min.	10 min.	1 min.	10 min.
100	14	17	12	16
500	13	17	12	12
1,000	10	14	11	12

■ Results



(a) MD5 algorithm



(b) SHA-1 algorithm

Secure ICWSN with light-weight blockchain

- Advantages of the blockchain (BC)-based secure ICWSN:
  - The users can identify the verified caching data without central brokers.
  - The BC architecture protects it from the risk of being a single point of failure when the ledger faces malicious attacks.
  - The users do not need additional verifications for the data in BC.
- Technical issues:
  - Typical BC require iterative hash calculations, such as PoW (Proof-of-Work).
  - Exhaustive computer calculations are not realistic for WSNs because the nodes are generally resource-constrained.

▼

- We proposed a light-weight verification scheme for secure ICWSNs [13][14][15][16].
- We focus on the consensus scheme suitable for ICWSNs, but its concept differs from traditional BCs, i.e., the proposed scheme does not use a lightweight node (wallet) that has a portion of the functions and stored data.

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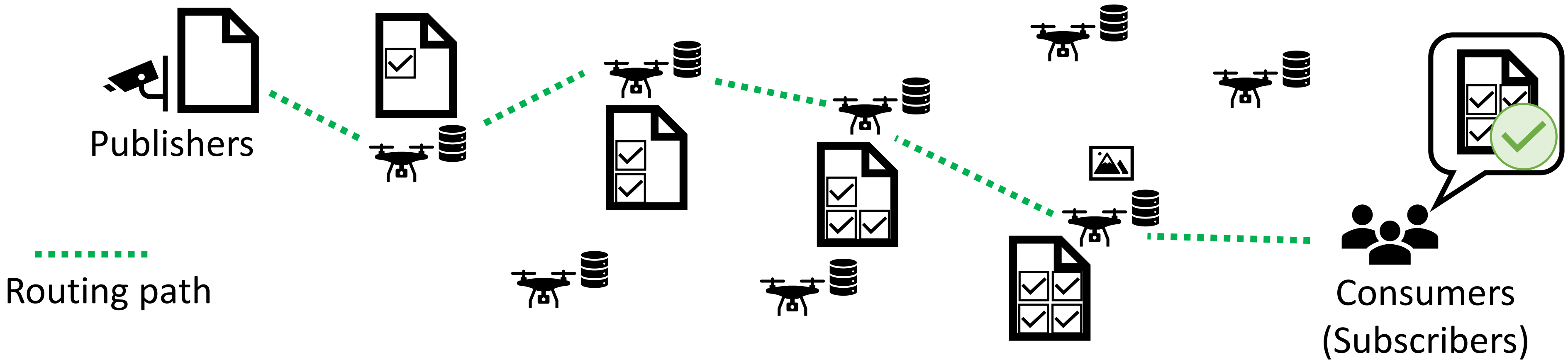
[13] S. Mori, "A study on lightweight BC-secure caching scheme for ICN-UAV-WSNs," *Proc. RISP NCSP,* 2019.

[14] S. Mori, "A fundamental analysis of caching data protection scheme using light-weight BC and hashchain for ICWSNs," *Proc. BRAINS*, 2020.

[15] S. Mori, "Caching data protection scheme for ICWSNs," *Proc. IARIA ICN,* 2020.

[16] S. Mori, "Secure caching scheme using BC for UAV-ICWSNs," *J. Signal Process.*, **26**, 1, pp. 21–31, 2022.

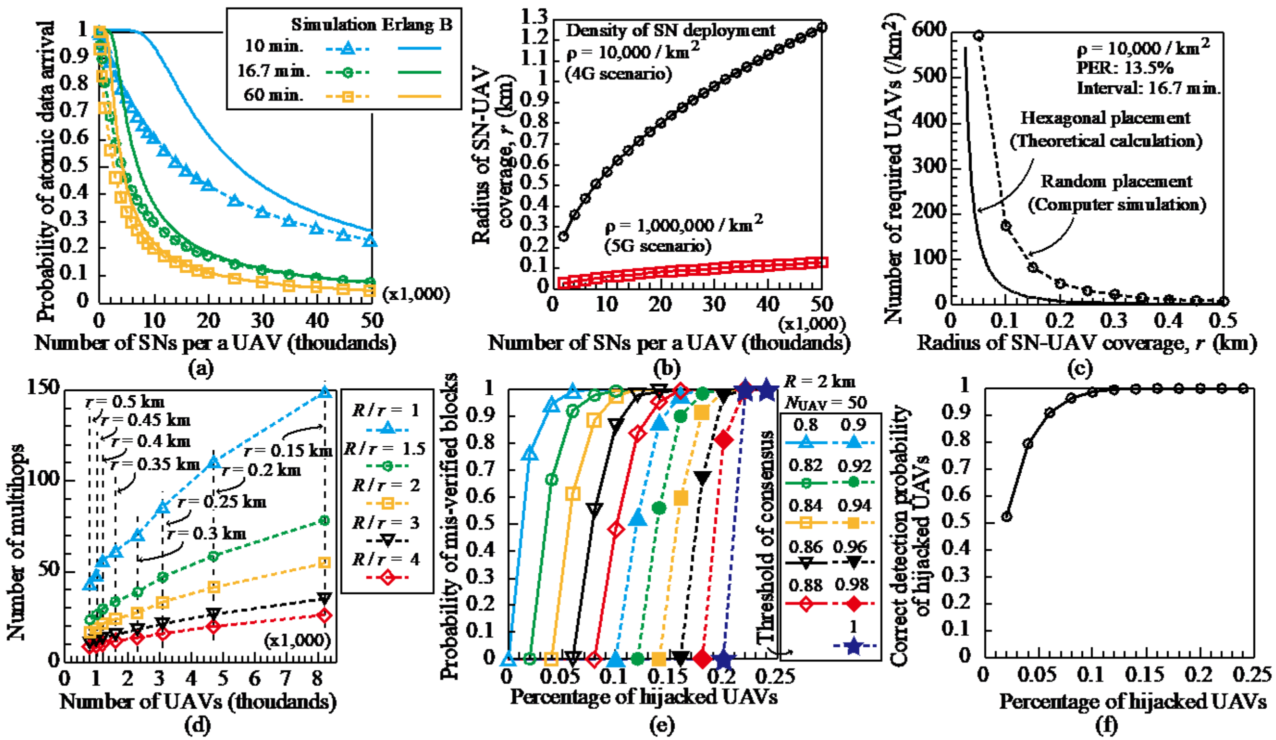
Secure ICWSN with light-weight blockchain



- The proposed scheme uses a voting-based verification method.
  - The data are forwarded among aerial relay nodes in multi-hop wireless networks, and the nodes are assigned to validators.
  - In the verification process, the data are signed when the validators have confirmed and verified the data.
  - We can regard the data as correctly verified if the data can obtain sufficient signatures (for example, 80% in Ripple crypto-currency).
- The proposed scheme uses the hashchain-based signature in (3).
  - By decoding hash-chain-based signatures, consumers can verify the data's traceability and stability for the validators.

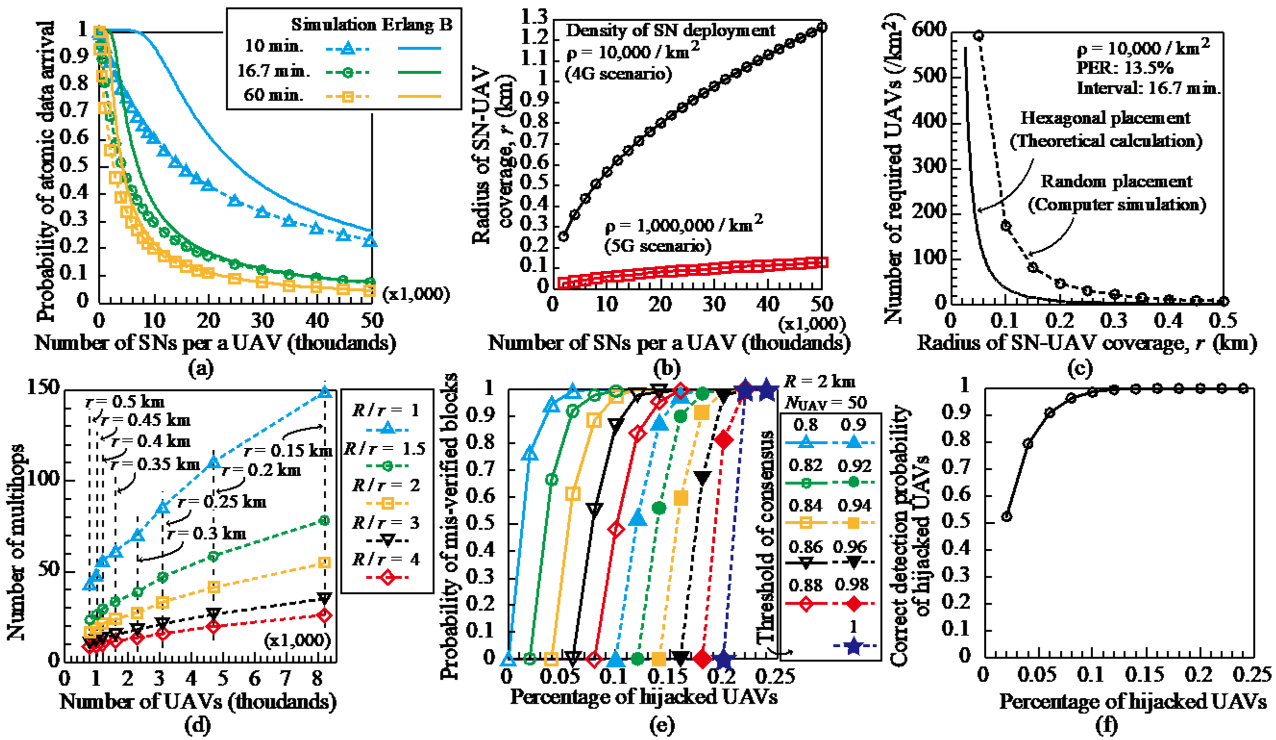
$$s_m = \mathcal{H}_n \left(D_{m-1} \oplus s_{m-1}\right) = \mathcal{H}_n \left(\mathcal{H}_{n-1} \left(\cdots \mathcal{H}_2 \left(\mathcal{H}_1 \left(x_0\right)\right)\right)\right) \quad (3)$$

Secure ICWSN with light-weight blockchain



- Simulation environments:
  - The computer simulator was implemented using C++.
  - Computer simulations were performed on the PC (Windows 10 OS, Intel Core i5-9400 (2.9GHz) CPU, and 16 GB RAM).
  - Sensor nodes are deployed in a 100-km^2 area, and the simulation parameters were decided based on Japan's low-power wide-area (LPWA) specifications.

Secure ICWSN with light-weight blockchain



- Results and discussions:
  - If data should be obtained by 80% consensus, the scheme cannot work in typical 4G/5G WSN scenarios (a–d).
  - The scheme is available for 50 UAVs with 2 km coverage (e).
  - The malicious UAVs can be identified thanks to hash-chain-based signatures (f).
- We can overcome the remaining issues by using novel technologies for UAV-ICWSNs in medium access control (MAC) and physical (PHY) layers.

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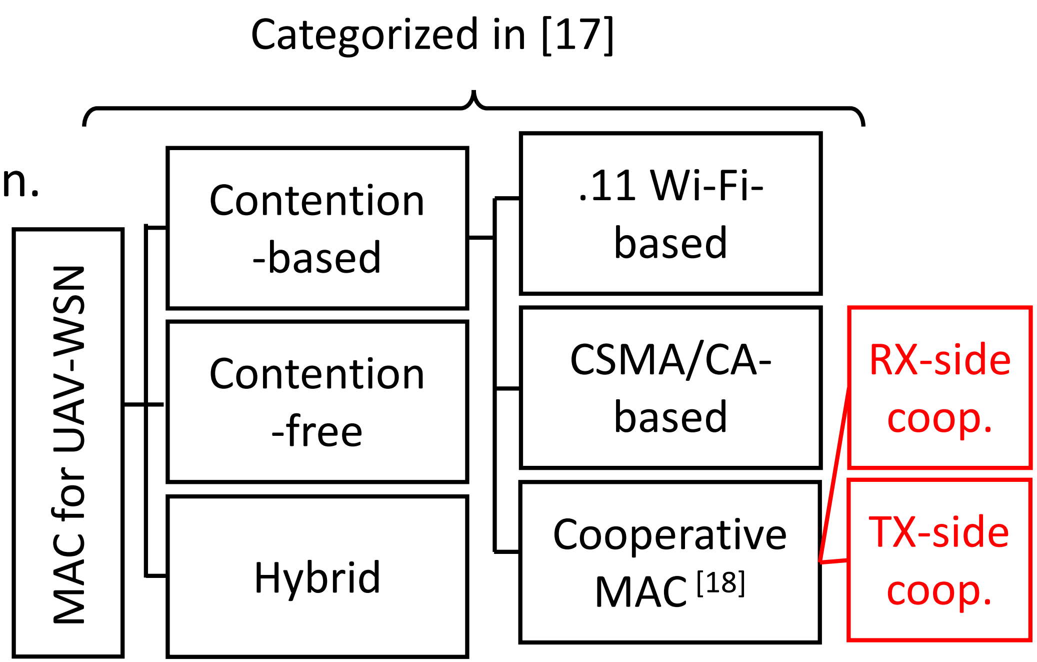
MAC layer design for ICWSNs

- We found that the proposed UAV-assisted ICWSN scheme could not work effectively in the typical 4G/5G WSNs because of heavy data traffic.

- A survey paper [17] categorized the MAC layer design in UAV-assisted WSNs.
- In our study [18], a cooperative MAC protocol was proposed.

- Using the knowledge [18], we investigated a MAC and PHY design.
  - The proposed scheme uses an erasure code with cross-layer optimization.
  - The scheme assumes the nodes with dual-bands.



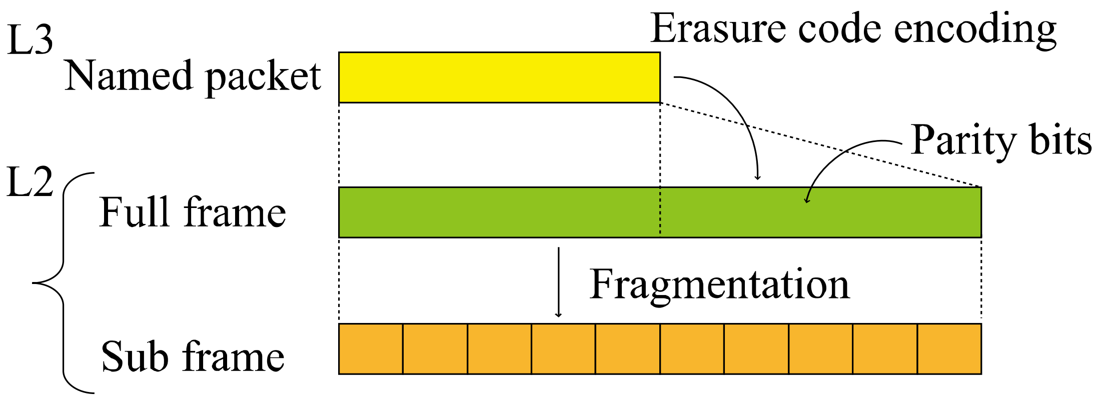
[17] S. Poudel, et al., "MAC protocols for UAV-aided WSNs: A survey," *IEEE Access*, **7**, pp. 65728–65744, 2019.
[18] S. Mori, "Cooperative sensing data collecting framework by using UAV in WSN," *Proc. IEEE ICC,* 2016.

MAC layer design for ICWSNs

- Error control code (ECC) can detect and correct the error bits.
- At the same time, ECC can be used as an erasure code.

- As an erasure code, the proposed scheme [19][20] selected low-density parity-check (LDPC) code and the Reed-Solomon (RS) code.
- In short, named data are encoded using erasure codes; hence, the data can be decoded and restored even if all chunks are not completely received.

- The consumer can recover the data based on any chunks from neighbors.
- The number of retransmissions can be reduced.



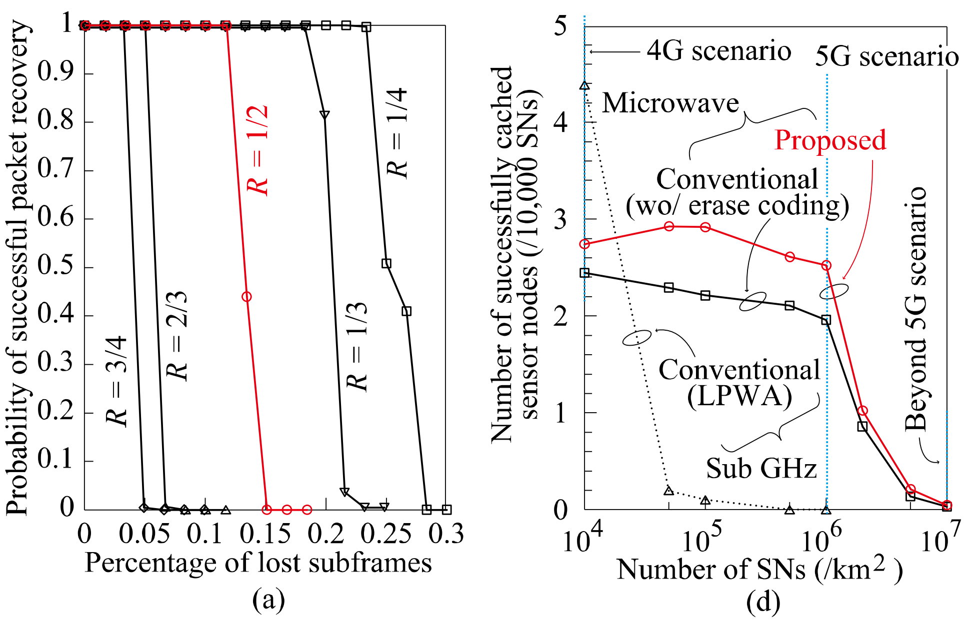
[19] S. Mori, "A fundamental analysis of an erase code-enabled data caching scheme for future UAV-IC-WSNs," *Proc. IARIA ICN*, 2021.

[20] S. Mori, "Data collection scheme using erasure code and cooperative communication for deployment of smart cities in ICWSNs," *Int. J. Adv. in Netw. & Serv.*, **14**, 3&4, pp. 54–64, 2021.

MAC layer design for ICWSNs

- As the robustness of erasure code, the data can be restored under the code rate, R, was

R	1/4	1/3	1/2	2/3
Number of lost chunks	11	7	3	2



Simulation parameters

Terms	Values
Erasure code	LDPC [1)] with sum-products decoding
Trans. Interval	600 s (= 10 min.)
Multiple access	Slotted-ALOHA
Number of channels	15
Full-frame length	64,800 bit
Number of fragmentations	60
Modulation method	BPSK
Error control coding	Convolutional coding
Radio Frequency	2.4 GHz (in microwave), 920 MHz (in sub-GHz)
Channel model	Rayleigh fading
Radio propagation model	Erceg's model (SN-BS), Amorim's model (SN-UAV)
Transmission power	0 dBm
Antenna gain	0 dBi
Circuit loss	0 dB
Thermal noise	−172 dBm

1) The LDPC code's parity-check matrix is decided based on DVB-S2.

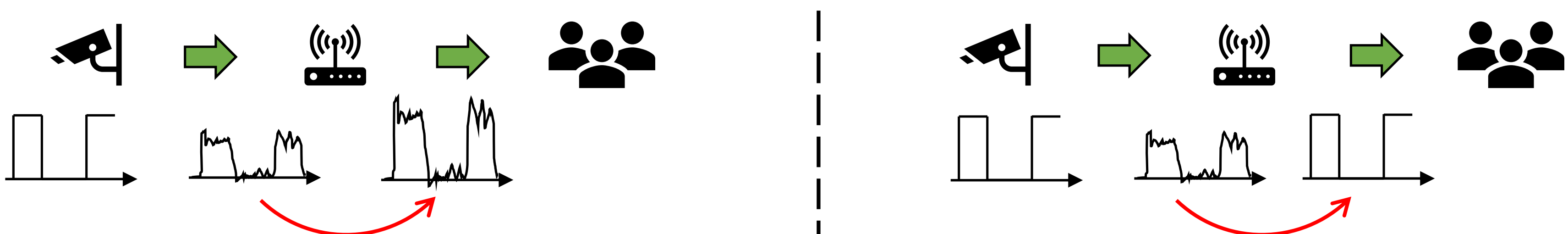
- The number of SNs is given by 10,000/km^2 (4G), 1,000,000/km^2 (5G), and 10,000,000/km^2 (B5G) for deployment scenarios, respectively.
- The proposed scheme can work under the 5G scenario (d).

PHY layer design for ICWSNs

- ICWSN is a broadcast-based communication (multi-path network).
- The proposed scheme [21][22] uses network coding (NC) on the relay node and constructive interference during data flooding.

■ Classification of relay communications:

- ‣ In the amplify-and-forward method, the received signal is amplified and forwarded.
- ‣ In the decode-and-forward method, if the received signal is correctly decoded, it is re-encoded and forwarded.

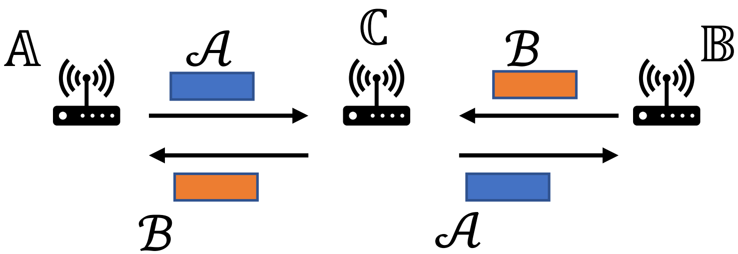


Amplify-and-forward method **Decode-and-forward method**

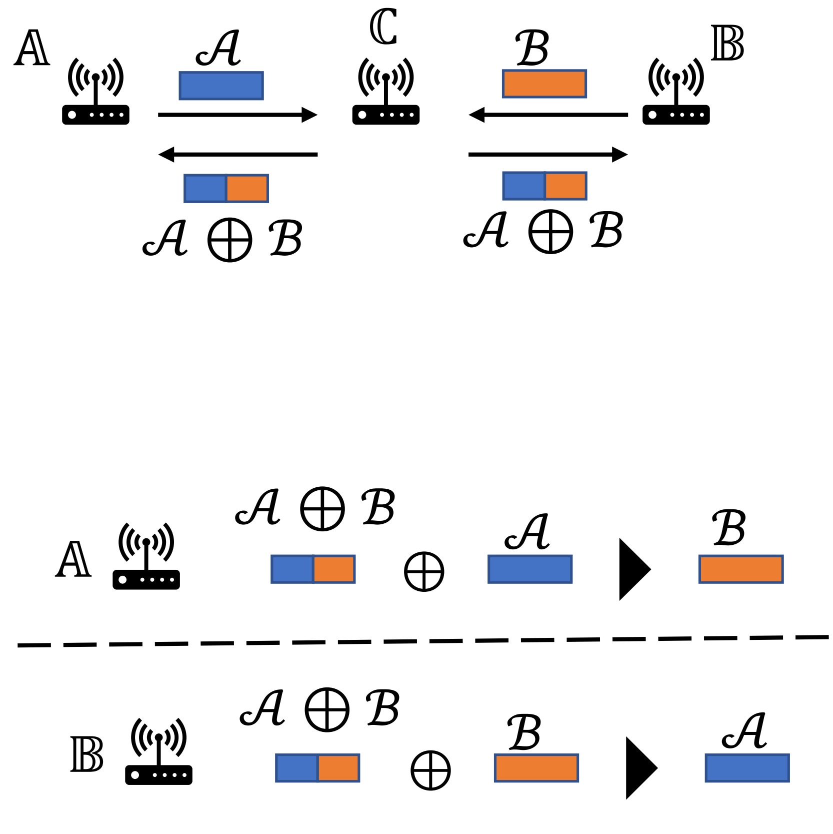
[21] S. Mori, "Cooperative communication scheme using network coding and constructive-interference phenomena for ICWSNs," *Proc. IARIA ICN*, 2022.

[22] S. Mori, "A cooperative and coded communication scheme using network coding and constructive interference for ICWSNs," *Int. J. Adv. in Netw. & Serv.*, **15**, 3&4, pp. 54–61, 2022.

PHY layer design for ICWSNs



General relay

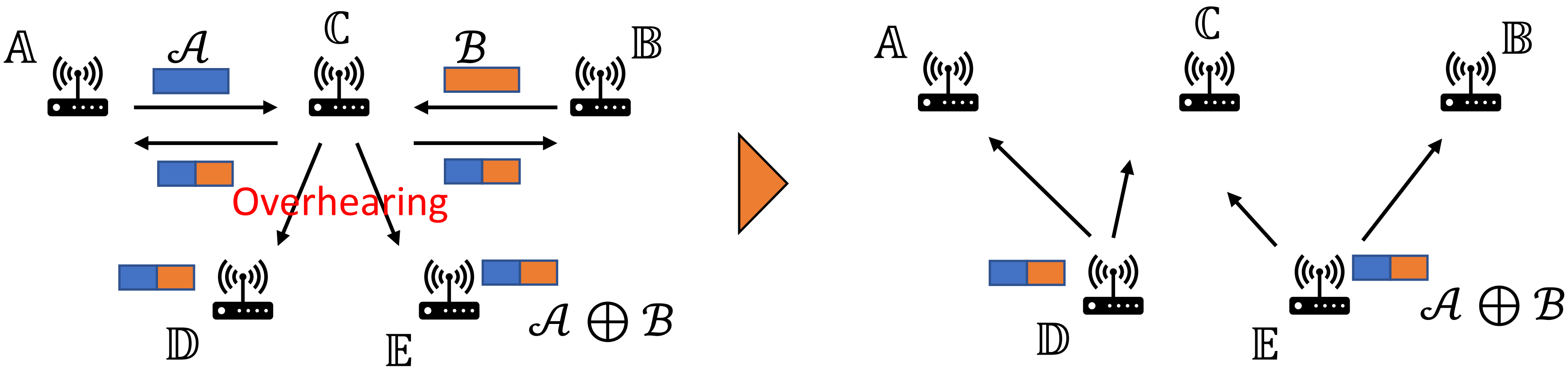


NC-based cooperative relay

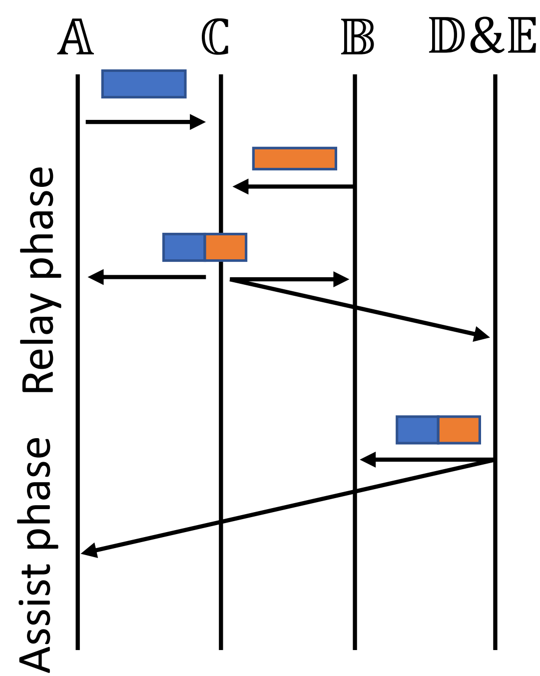
- General relay:
  1. Sending $\mathcal{A}$ from $\mathbb{A}$ to $\mathbb{C}$
  2. Sending $\mathcal{B}$ from $\mathbb{B}$ to $\mathbb{C}$
  3. Forwarding $\mathcal{A}$ from $\mathbb{C}$ to $\mathbb{B}$
  4. Forwarding $\mathcal{B}$ from $\mathbb{C}$ to $\mathbb{A}$
- NC-based cooperative relay:
  1. Sending $\mathcal{A}$ from $\mathbb{A}$ to $\mathbb{C}$
  2. Sending $\mathcal{A}$ from $\mathbb{B}$ to $\mathbb{C}$
  3. Forwarding $\mathcal{A} \oplus \mathcal{B}$ from $\mathbb{C}$ to $\mathbb{A}$ and $\mathcal{B}$.

- When relay nodes transfer the bit-by-bit mixed data by utilizing an XOR operation, $\oplus$, the data transmission procedure can be reduced to three steps.

PHY layer design for ICWSNs

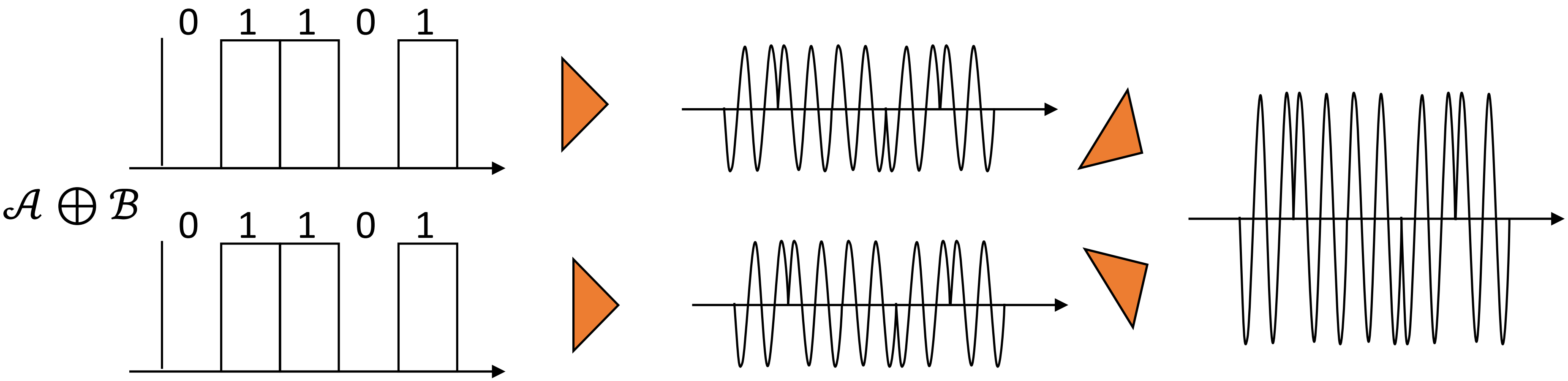


- When ℂ forwards NC data, 𝔻 and 𝔼 around ℂ can also receive it by overhearing.
- The proposed scheme includes an assist phase, in which 𝔻 and 𝔼 help the NC data transfer in place of ℂ.

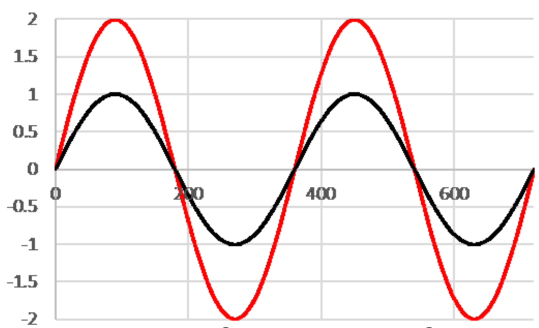


- In the assist phase, the NC data are conflicted at the same time and neighbor area.
- The proposed scheme uses constructive interference to cancel the interference between them.
- In other words, the phenomena effectively work in this scenario.

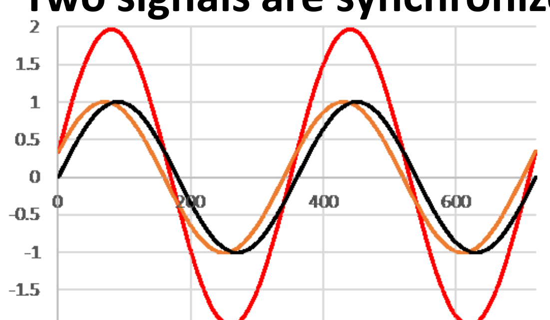
PHY layer design for ICWSNs



Transmitter-side node **Receiver-side node**

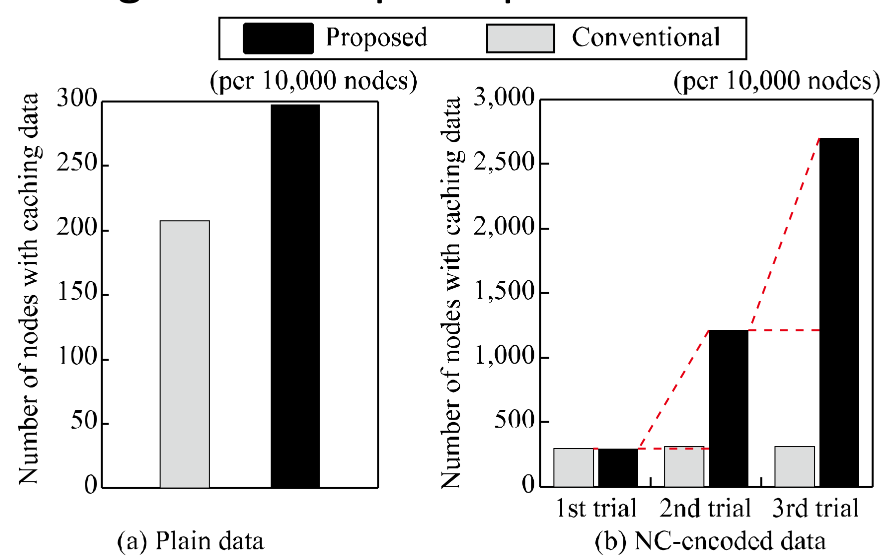


Two signals are synchronized



Two signals are slightly offset

- If the same data is synchronously transmitted, the receiver does not experience mutual interference because the signals are superimposed on each other.

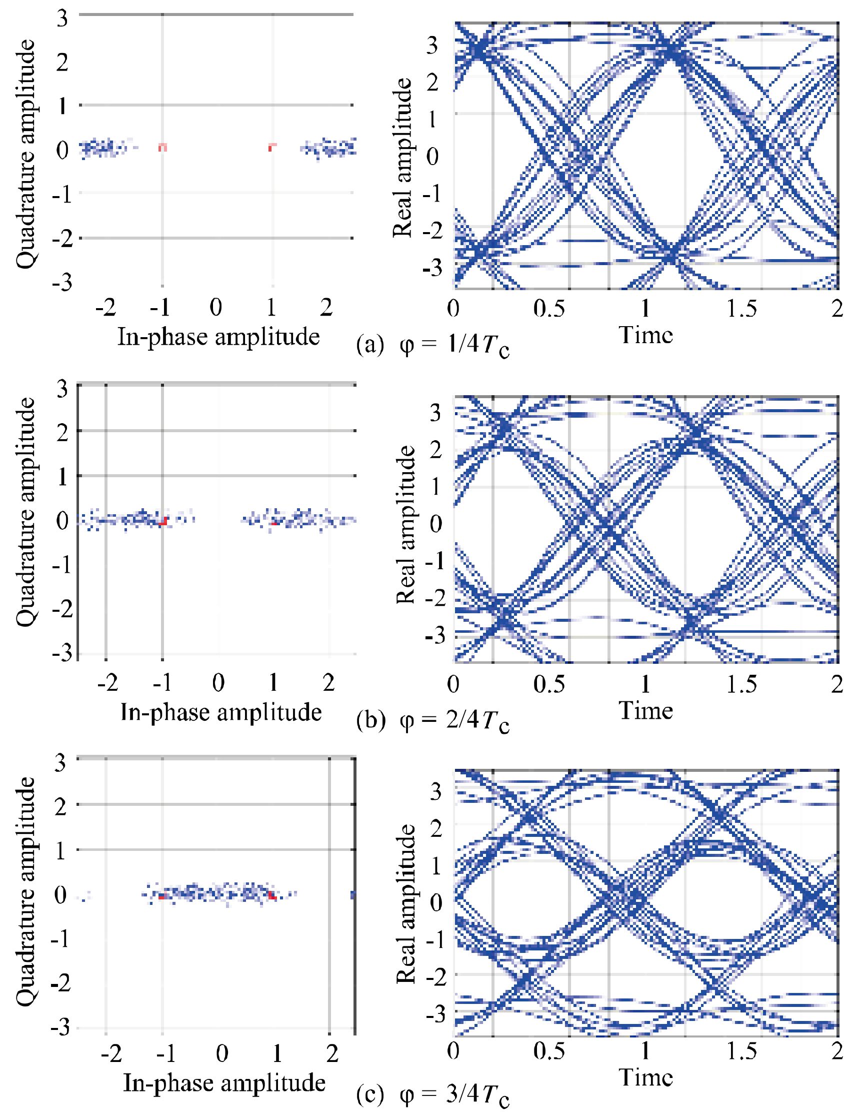


PHY layer design for ICWSNs

- If the transmission timing is relatively delayed, the signal will be distorted.
- In another computer simulation, we evaluate signal recoverability.
- The results show that the proposed scheme can separate the signal constellations and represent the clear eye patterns, which the receiver can be correctly demodulated.

Simulation parameters

Terms	Values
Frame length	1,000 bit
Error-control coding	N/A
Modulation method	Binay phase shift keying with Gray mapping rule
Detector’s decision type	Hard-decision
Carrier-signal filter	Raised cosine (square root) Rolloff factor: 0.22, Span: 12 symbol
Sampling rate	4 samples/symbol
Channel model	Additive white Gaussian noise
Signal-to-noise ratio	Relay node: 20 dB, Assist node: 20 dB



Receiver-side detector’s performance, including constellation patterns and eye diagram, for received signals.

Agenda

- Introduction
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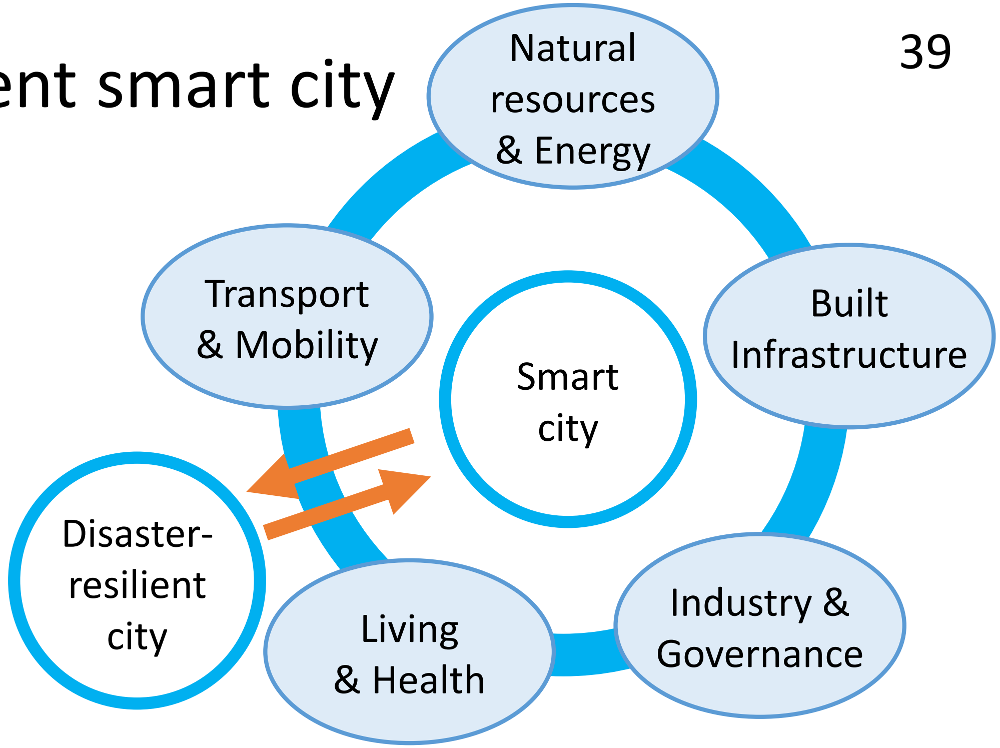
    Question: What services will you use ICWSN for?
    Answer: We apply it to various services underpinning smart cities.

  - Application services for ICWSNs
    - ICWSNs for disaster-resilient smart cities
    - Green ICWSNs for sustainable smart cities
  - Ecosystem development for smart-city-as-a-service framework
- Conclusions

ICWSNs for disaster-resilient smart city



- Smart cities provide intelligence to various aspects of daily life for rapid urbanization, such as smart homes, personal healthcare, and urban infrastructure.
- Smart cities can solve the issues of not only urban sophistication but also resilience to disasters.

- Smart-city technologies usually provide daily services; whereas the disaster information are shared using the same system.
- Advantages of the proposed concept:
  - Economic efficiency (i.e., we cannot construct the disaster communication and networking system)
  - Availability (i.e., the system always works, even in an emergency).
- As a first case study, we investigated a river-monitoring system [23].

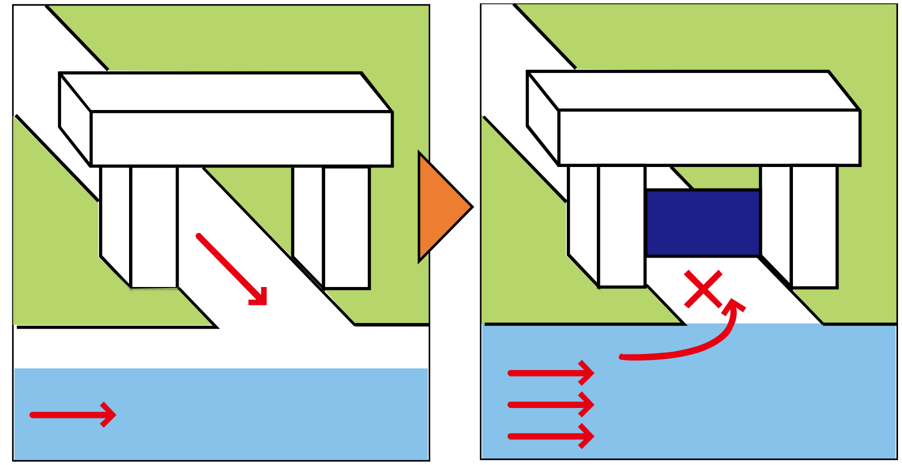
[23] S. Mori, "Prototype development of river velocimetry using VPIV for smart cities and disaster area networks," *Proc. ISCIT*, 2021.

ICWSNs for disaster-resilient smart city

- Nogata (Fukuoka, Japan)
  - Nogata is a rural city in the northern Kyushu island area.
  - In the 1870s-1960s, the city prospered from the coal industry near the Chikuho coalfield, the largest mining area in Japan.
  - Nowadays, the city center is a compact area with a good balance of commercial, agricultural, and industrial development.
- The Onga River flows in the central area and suffers from overflows.

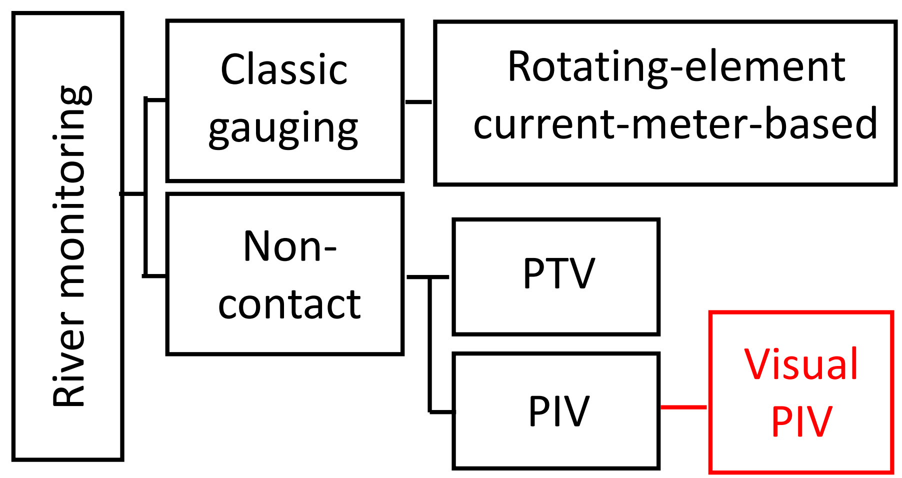
ICWSNs for disaster-resilient smart city

- In Nogata, the water gates need to be opened and closed based on fluid velocity and direction to prevent backflow into the branch rivers.
- We aimed to obtain a fluid velocity and direction without any physical contact.



When the river level rises, water gate must be closed.

- For this perspective, in river sensing technologies, visual particle image velocimetry (VPIV) was studied [24].
- We developed a VPIV-based ICWSN testbed device and demonstrated the system's feasibility [23].

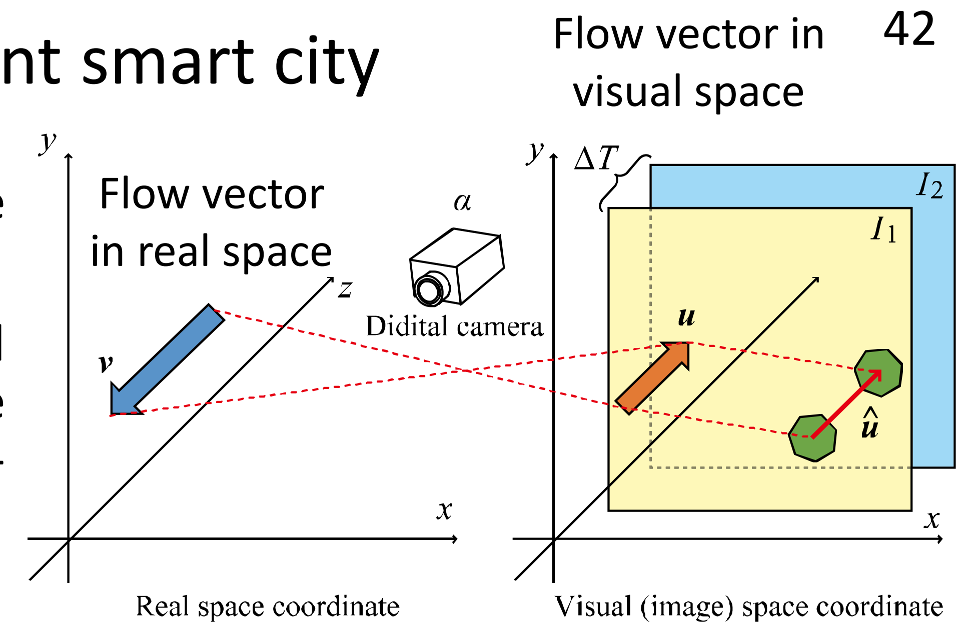


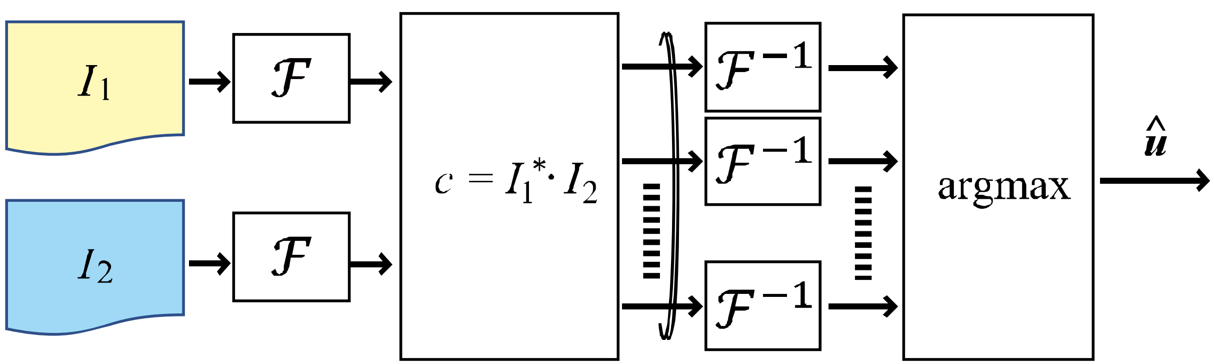
[24] I. Fujita, et al., "Large-scale PIV for flow analysis in hydraulic engineering applications," *J. Hydraulic Research*, **36**, 3, pp. 397–414, 1998.

[23] S. Mori, "Prototype development of river velocimetry using VPIV for smart cities and disaster area networks," *Proc. ISCIT*, 2021.

ICWSNs for disaster-resilient smart city

- The real river-flow vector can be estimated from that of visual space.
- The river-flow vector in the visual space can be calculated based on the cross-correlation between two time-lapse images.





Procedure of the VPIV method

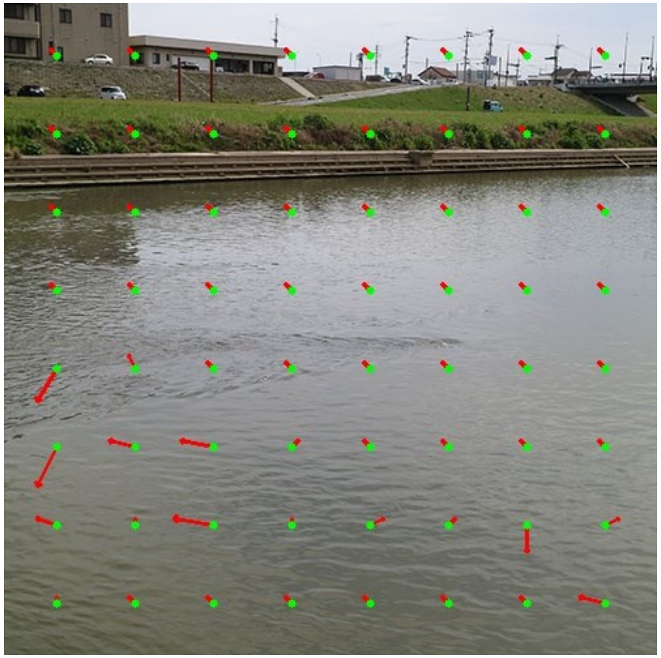
- To accelerate the correlation calculation, the VPIV method converts the data from the time domain to the frequency domain using the two-dimensional fast Fourier transform (FFT).

ICWSNs for disaster-resilient smart city

- The calculation program of the VPIV-based river-flow vector was implemented using C++.
- The developed testbed can estimate the visual river-flow vectors for almost all points.
- The average ΔX and ΔY were 2.69 pixels and 3.34 pixels, respectively, for 500 pairs of images.

Field view of testing site

■ Example of experimental results



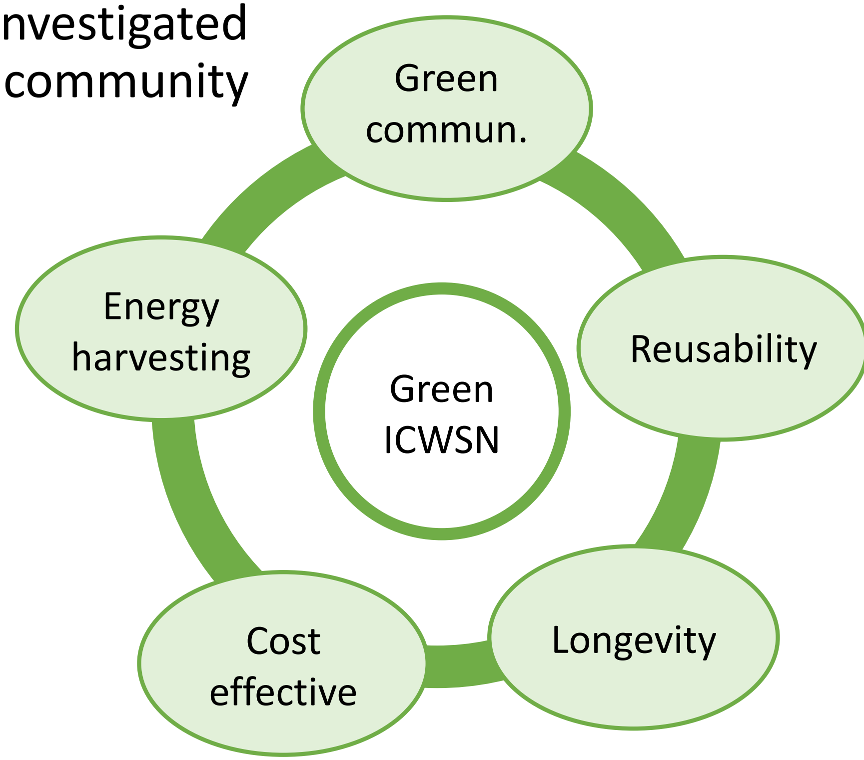
Specifications of analysis images

Frame rate	ΔT = 100 ms
Image size	500×500 pixels
Resolution	72 dots/inch

Green ICWSNs for sustainable smart city

- The deployment of smart-city applications is not a primary cause of greenhouse emissions.
- Massive WSN devices and ubiquitous connectivity can potentially create a carbon footprint.
- Many energy-efficient technologies are investigated for zero-carbon smart cities, and the community considers it a hot topic. [25][26].

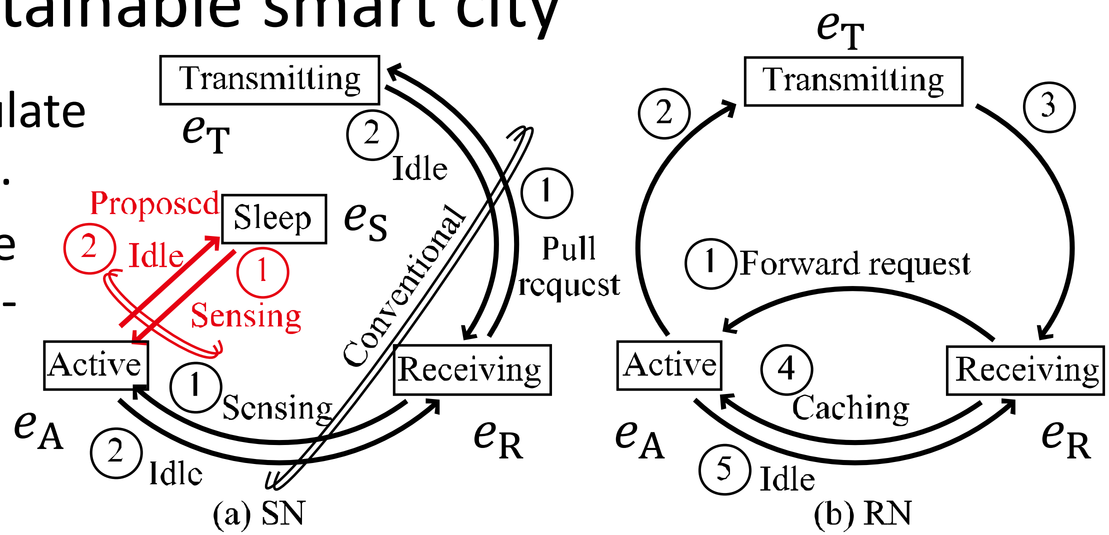
- ICWSNs can make the systems green as a secondary goal.
  - ICWSNs do not transmit all data (pull operation).
  - The network provides an in-network caching scheme.



[25] S. Verma, et la., "Toward green communication in 6G-enabled massive Internet of things," *IEEE IoT J.*, **8**, 7, pp. 5408-5415, 2021.
[26] S. Sarkar, et al., "Green IoT: Design goals, challenges and energy solutions," *Proc. ICCES*, 2021.

Green ICWSNs for sustainable smart city

- In our studies [27][28], 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 [27][28], 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.

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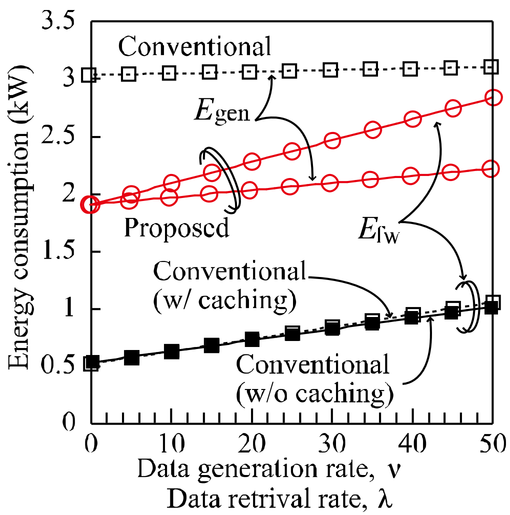
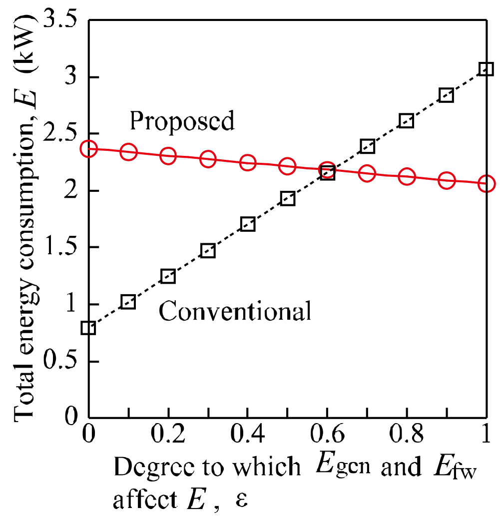
[27] S. Mori, "A preliminary analysis of data collection and retrieval scheme for green ICWSNs," *Proc. ACM SIGCOMM WS NET4us*, 2022.

[28] S. Mori, "Energy-efficient cooperative caching scheme for Green ICWSN: Preliminary analysis and testbed development," *Proc. ACM MobiCom WS NET4us*, 2023.

Green ICWSNs for sustainable smart city

■ Numerical results





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

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

(w/o caching)

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

(w/ caching)

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

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

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

- Computer simulators were implemented using C++.
- The nodes were randomly distributed across the area.
- The simulation was considered the worst case.

▼

- 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

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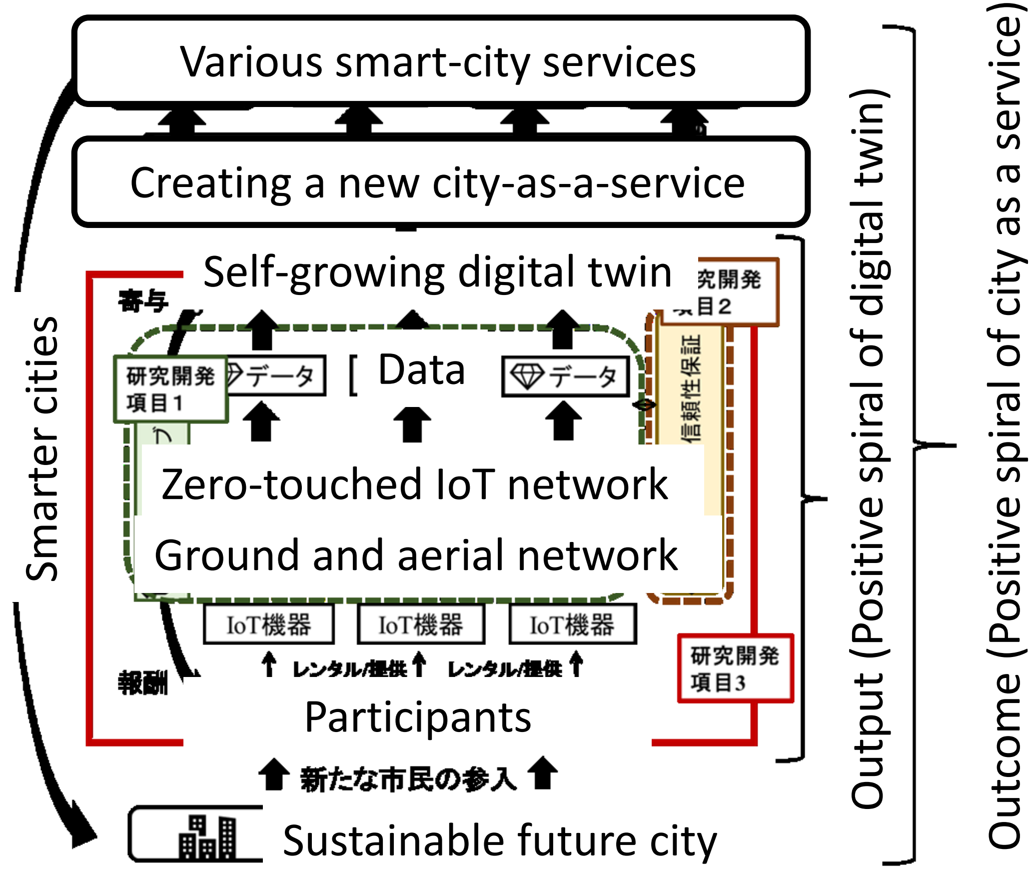
Ecosystem development for smart-city-as-a-service

- A city-level digital twin is a new starting point for advanced smart-city construction.
- In future cyber-physical systems, the sensing data will be gathered from WSNs and analyzed using artificial intelligence.

- To support the above objective, we will establish a new network and data management framework to provide a co-creative digital-twin eco-system [29][30].



Overview of proposed co-creative digital-twin eco-system.

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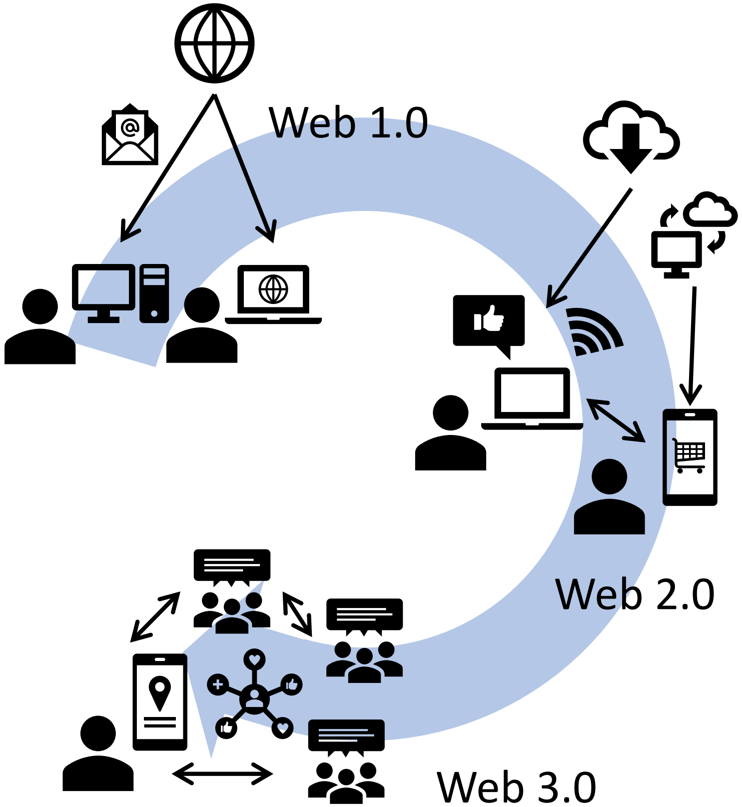
[29] D2EcoSys PJ: https://d2ecosys.org/ (retrieved: May 2024).

[30] K. Kanai, et al., "(Invited) D2EcoSys: Decentralized digital twin EcoSystem empower co-creation city-level digital twins," *IEICE Trans. Commun.*, **E107-B**, 1, pp. 50–62, 2024.

Ecosystem development for smart-city-as-a-service

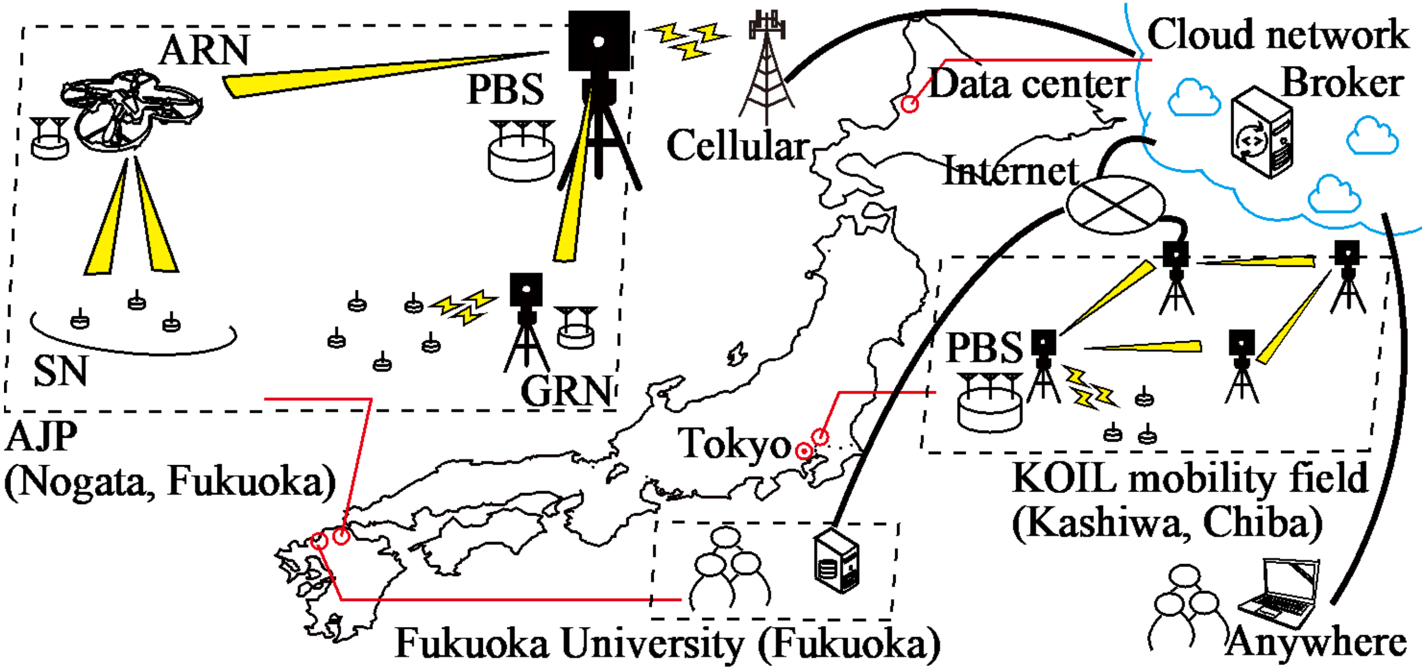
- In our ongoing project, we investigate a secure ICWSN framework [31][32][33][34].
- We will achieve a reliable ICWSN.

- The proposed scheme will be able to improve the availability of the network.
- We will implement a prototype device, develop a test field, and demonstrate using them.



[31] S. Mori, "ICWSNs for smart-city-as-a service: Concept proposal, testbed development, and fundamental evaluation," *Proc. IEEE CCNC*, 2023.
[32] S. Mori, "A preliminary evaluation of mmWave communications for ICWSNs," *Proc. RISP NCSP*, 2023.
[33] S. Mori, "Test-field development for ICWSNs and preliminary evaluation for mmWave-band wireless communications," *Proc. IEEE CCNC*, 2024.
[34] S. Mori, "ICWSN for decentralized and co-creative digital twin eco-system," *Proc. NCSP*, 2024.

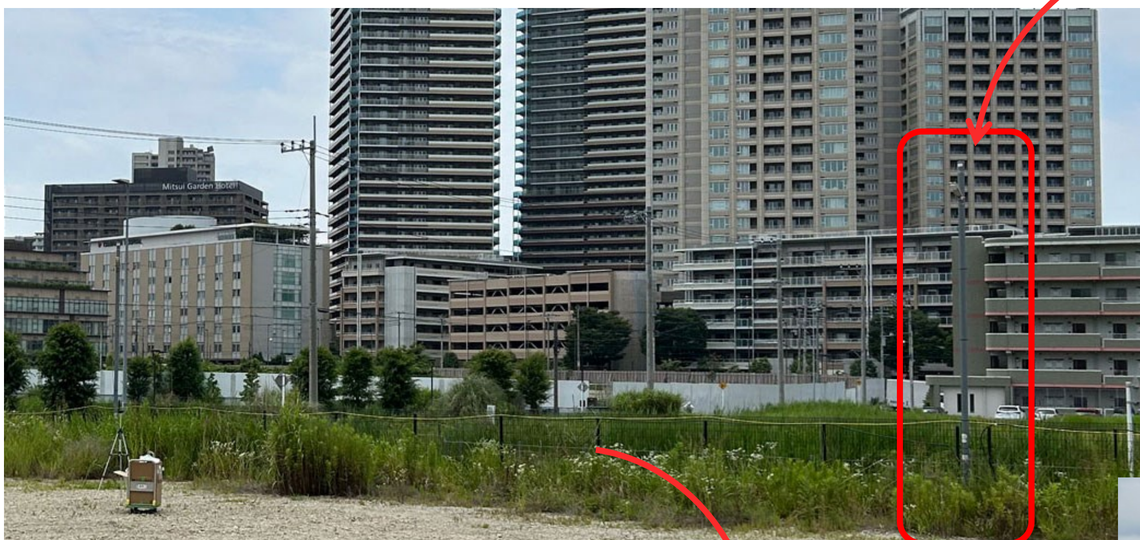
Proposed ICWSN framework



- The proposed framework can integrate and manage widely distributed ICWSNs.
- The test fields are constructed in Advantech Japan's baseball field (Nogata, Fukuoka) and KOIL mobility field (Kashiwa, Chiba).
- These fields and Fukuoka University are interconnected via the cloud network.
- ICWSN consists of sensor nodes (SNs), relay nodes (RNs), and a private base station (PBS).
- RN can be classified into ground RNs (GRNs) and aerial RNs (ARNs) on UAVs.

ICWSN test-field development

- KOIL Mobility Field (Kashiwa, Chiba)
  - The node device with integrated PBS and GRN was placed and connected to the Terragraph network deployed in the KOIL mobility field.



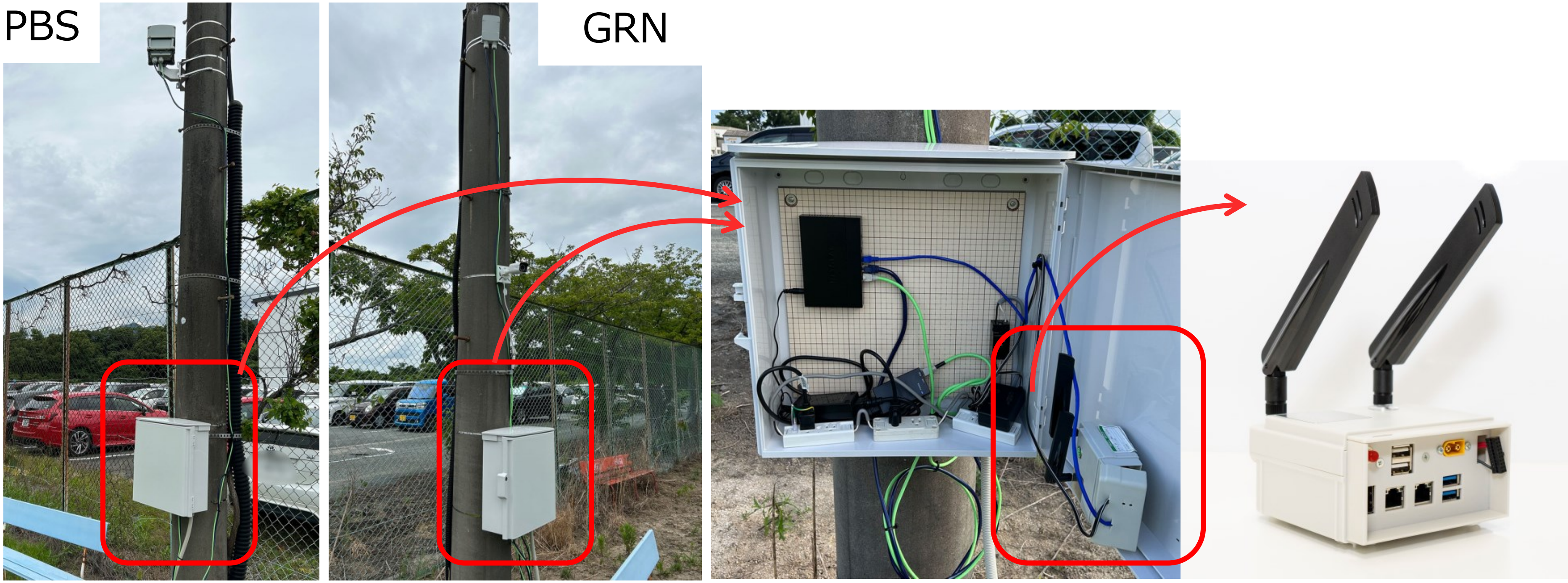
https://www.mitsuifudosan.co.jp/corporate/news/2021/0610_01/

ICWSN test-field development

- Advantech Japan’s baseball field (Nogata, Fukuoka)

- Our studies have focused on the baseball field since we experimented here.
- We will provide an example of the effort in another presentation as follows:
  - S. Mori, “MmWave UAV-assisted information-centric wireless sensor network for disaster-resilient smart cities: Preliminary evaluation and demonstration,” *Proc. IARIA ICN 2024*, Barcelona, Spain, May 2024.

ICWSN test-field development



- We implemented the PBS and RN.
- The control computer uses an industrial Advantech BUD (two-core 1.8 GHz Intel Atom CPU, 4 GB RAM, Ubuntu 20.04 OS) device for reliability and robustness.

Specification of Advantech BUD device

CPU	Intel Atom E3930 (2core)
Memory	LPDDR4-2400 4 GB
SSD	SATA SSD 32 GB
OS	Ubuntu 20.04 LTS
Modules	Intel AI*1 and cellular*2
Power supply	3-cells lithium-ion battery

*1 M.2 2230 Edge AI acceleration module with One Intel Myriad X

*2 LTE/HSPA+/GPRA module with GPS for JP

Conclusions

- Overview of the information-centric wireless networking
- Research activities:
  - Effective caching scheme for ICWSNs
  - Secure caching scheme with blockchain for ICWSNs
  - MAC and PHY design for ICWSNs
  - Application services for ICWSNs, including ICWSNs for disaster-resilient smart cities and Green ICWSNs for sustainable smart cities
  - Ecosystem development for smart-city-as-a-service framework
- We plan to exhibit our air-to-ground integrated ICWSNs in Japan Drone 2024.
  - https://ssl.japan-drone.com/
  - Dates: June 6–7, 10am–5pm
  - Venue: Makuhari Messe (Chiba, Japan)
  - Organizer: Japan UAS Ind. Dev. Assoc.

Thank you for your attention.

- This work was partly supported by NICT Japan (No. JPJ012368C05601) and JSPS KAKENHI (No. JP21H03436).
- We are grateful to Dr. Kenji Kanai for his helpful discussions, and Advantech Japan, BeMap, Haft, Panasonic, and TEAD for their help with the experiments.