IARIA ICN 2026
(Venice, Italy)

A Study on Delay-Sensitive Information-Centric Wireless Sensor and Actuator/Actor Networks

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福岡大學

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Fukuoka University

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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, information-centric wireless sensor networks, and their application for smart cities. He is an IARIA Fellow and a member of IEEE, ACM, IEICE, ISSJ, and RISP.

- Topics of research interest:
  - Smart-city applications (smart agriculture, smart industry, and digital twin)
  - Information-centric wireless sensor network w/ actuator and visual node
  - MmWaves, blockchains, non-terrestrial, secure, and green network
  - Delay-doppler (double selective) for joint radar (sensing) and commun.
  - Wireless communications and cross-layer design
- For more information, please see my website:
  - https://www.cross-layer.com/

Background

- For smart-city deployments, such as smart agricultures and smart industries, delay-sensitive Wireless Sensor and Actuator/Actor Networks (WSANs) are playing an essential role in future Internet of Things (IoTs).
  - Application services include environmental monitoring, remote sensing, and drone/robot controlling.
  - Various physical devices, such as temperature sensors, moisture detectors, pH sensors, and Global Positioning (Satellite) System (GPS) modules, are distributed throughout the field to gather real-time environmental data.
- WSANs consist of spatially distributed controllers, sensors, and actuators, in other word, WSANs are Wireless Sensor Network (WSN) with several actuators/actors.
  - In the spotlight on industrial and agricultural node devices, monitoring and control data should be forwarded and processed in real time (live streaming).
  - The data are collected and analyzed on a central cloud server to improve efficiency and safety, enabling task sharing and decision-making[1][2].

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[1] W. Liu et al., "On the latency, rate, and reliability tradeoff in wireless networked control systems for IIoT," *IEEE Internet of Things J.*, vol. 8, no. 2, pp. 723–733, Jan. 2021.

[2] N. Makondo et al., "Implementing an efficient architecture for latency optimization in smart farming," *IEEE Access*, vol. 12, pp. 140502–140526, Sept. 2024.

Background

- The data should be exchanged reliably, delay-sensitively, and efficiently across open, autonomous, and distributed areas with minimal human involvement.
- Information-Centric Networking (ICN) is a promising network architecture that shifts the networking model from host locations to transmitted information[3].
  - Host-centric networks generally exchange data based on addresses, such as Internet Protocol (IP) addresses, while ICN names the data, and named data are delivered directly based on their properties (names).
  - ICN natively enables in-network caching scheme for further data retrievals.
  - ICN can remove the single-route disruption failure issue and improve content delivery effectiveness thanks to multi-route deliveries.

- The ICN frameworks have been recently investigated in IoT platforms, which are also called Information-Centric Wireless Sensor Networks (ICWSNs) [4].
- This applies not only to WSNs but also Information-Centric WSANs (ICWSANs).

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[3] B. Ahlgren et al., “A survey of information-centric networking,” *IEEE Commun. Mag.*, vol. 50, no. 7, pp. 26–36, July 2012.

[4] Z. Zhang et al., “In-network caching for ICN-based IoT (ICN-IoT): A comprehensive survey,” *IEEE Internet of Things J.*, vol. 10, no. 16, pp. 14595–14620, Aug 2023.

Background

- Most studies in WSANs focus on control perspective.
  - Related studies oversimplify wireless network models that do not capture key parameters, such as latency, data rate, and reliability [5][6].
  - This paper focuses on how delay should be considered when adopting an ICN design instead of a traditional host-centric network design.
- For real-time and streaming data transmissions, on the receiver-side nodes, the data must be updated promptly to ensure its freshness, as outdated data can lose its value to users and be unsuitable for actuator controls.
- In the conventional scheme, the delay metric can be measured as the round-trip time using the Internet Control Message Protocol (ICMP)-compliant ping.
- Since ICN manages data by name, it does not explicitly determine which node will respond; therefore, its conventional metrics are not helpful.
  - Data retrieval of ICN does not necessarily require the source node to be data-providing, i.e., the data-requester-side node broadcasts a data-request (so-called interest) message to the network, and the node that stores the targeted data and closest to the requester answers.

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[5] S. Kim et al., “Real-time controller reconfiguration for delay-resilient cyber-physical systems,” IEEE Access, vol. 10, pp. 101220–101228, 2022.

[6] N. Finn, “Introduction to time-sensitive networking,” IEEE Commun. Standards Mag., vol. 6, no. 4, pp. 8–13, Dec. 2022.

Contribution

- To quantify data freshness, we propose a novel ICWSN/ICWSAN scheme that uses the Age of Information (AoI)[7] as a delay metric.
  - AoI is typically defined as the time elapsed since the data is generated.
  - The proposed scheme is expanding based on the previously developed ICWSN platform[8].
  - The contribution of this paper is to expand the AoI concept to ICWSANs, which has not been investigated in previous studies.
- For the types of related indicators, there have been slightly different definitions,
  - Age of synchronization: Time elapsed from when the transmitter updates data until the user receives the most recent data.
  - Effective AoI: AoI with active information updates for users.
  - Age of incorrect information: Time interval from the receiver's last receipt of the most recent data until the current time.
  - Age of outdated information: Time difference between the current time and the time when the data at the transmitter initially becomes outdated.

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[7] B. Yu et al., "Age of information for the cellular Internet of things: Challenges, key techniques, and future trends," *IEEE Commun. Mag.*, vol. 60, no. 12, pp. 20–26, Dec. 2022.

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

Related work

- Nagaraj et al.[9] investigated an industrial automation control system based on ICN and identified the requirements of industrial networks.
- Zhang et al.[10] investigated a mobile edge computing system for periodically collecting data, given the limited energy and computational capabilities.
- Zhao[11] investigated an unmanned aerial vehicle-assisted WSNs, in which a UAV periodically collected sensing data.
- Huang et al.[12] investigated the trade-off between latency and reliability in packet-length control for WSANs.
- Basnayaka et al.[13] analyzed a relay network with AoI for short packet communication to meet delay-sensitive requirements.

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[9] A. H. Nagaraj et al., “On the importance of traffic control subsystem in ICN-based industrial networks,” *Proc. IEEE ANTS 2020*, New Delhi, India, Dec. 2020, pp. 1–4, doi: 10.1109/ANTS50601.2020.9342792.

[10] G. Zhang et al., “AoI minimization for WSN data collection with periodic updating scheme,” *IEEE Trans. Wireless Commun.*, vol. 22, no. 1, pp. 32–46, Jan. 2023.

[11] M. Zhao et al., “Up-downlink AoI-driven multi-source data collection in UAV-assisted wireless sensor networks,” *IEEE Trans. Wireless Commun.*, vol. 24, no. 2, pp. 1178–1192, Feb. 2025.

[12] K. Huang et al., “Wireless feedback control with variable packet length for industrial IoT,” *IEEE Wireless Commun. Lett.*, vol. 9, no. 9, pp. 1586–1590, Sept. 2020.

[13] C. M. W. Basnayaka et al., “DataAge: Age of information in SWIPT-driven short packet IoT wireless communications,” *IEEE Internet of Things J.*, vol. 11, no. 16, pp. 26984–26999, Aug. 2024.

Network model

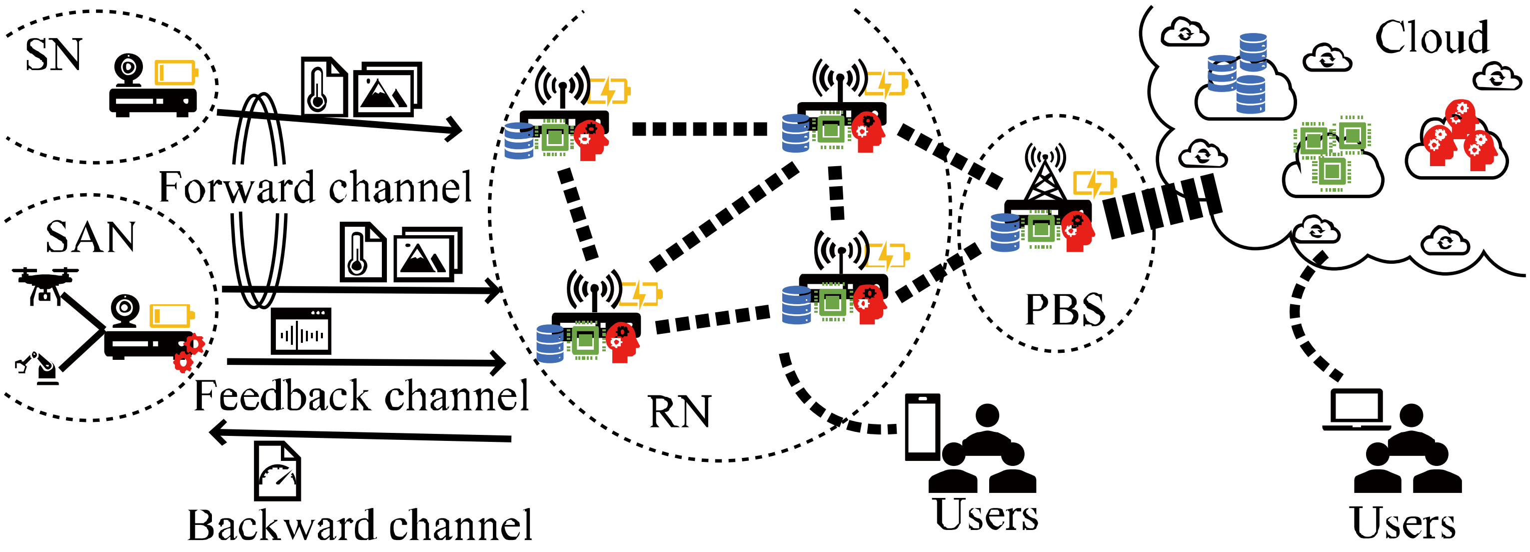


Figure 1. Network model of proposed scheme

- Figure 1 shows the network model of the proposed scheme.
  - Network nodes consist of Sensor Nodes (SNs), Sensor and Actuator/Actor Nodes (SANs), Relay Nodes (RNs), and Private Base Station (PBS).
  - Assuming that SN and SAN can access the nearest RN with a single hop.
  - In SANs, the sensor and the actuator/actor are co-located at the same node to simplify exposition, but this need not be the case in reality.
  - PBS includes RN functionality and a proxy for external networks, and a portion of the sensing data is shared with the cloud if necessary.
  - There are two types of users: internal and external network users.

Network model

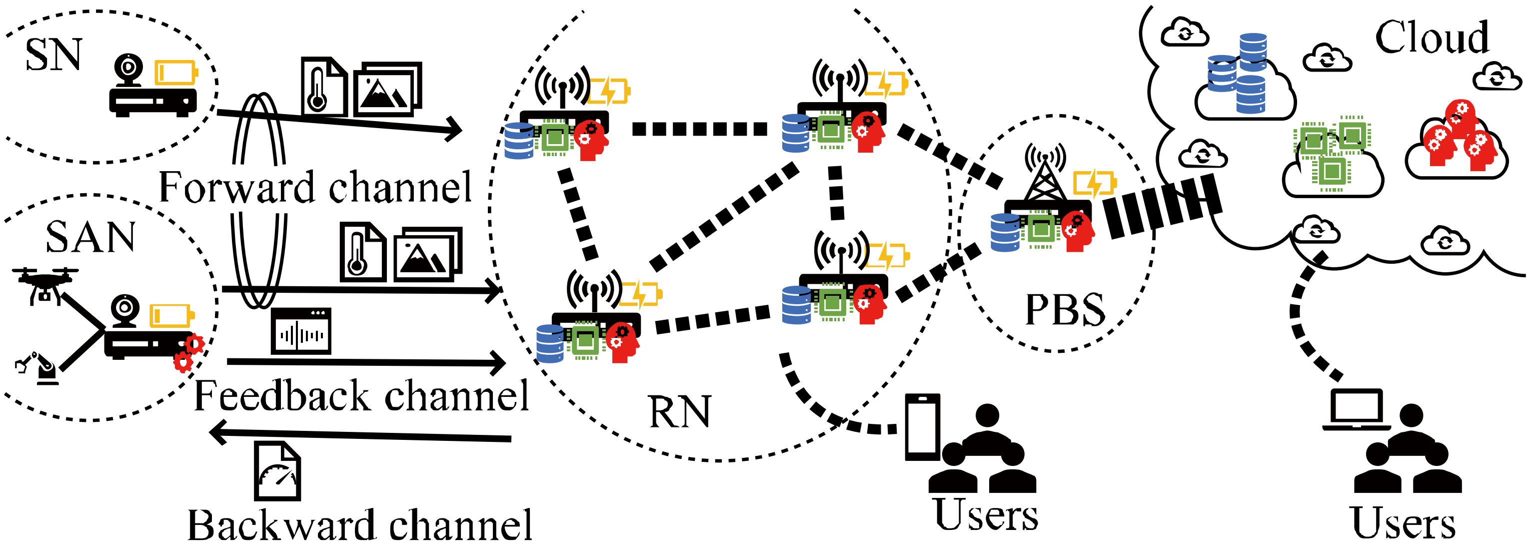
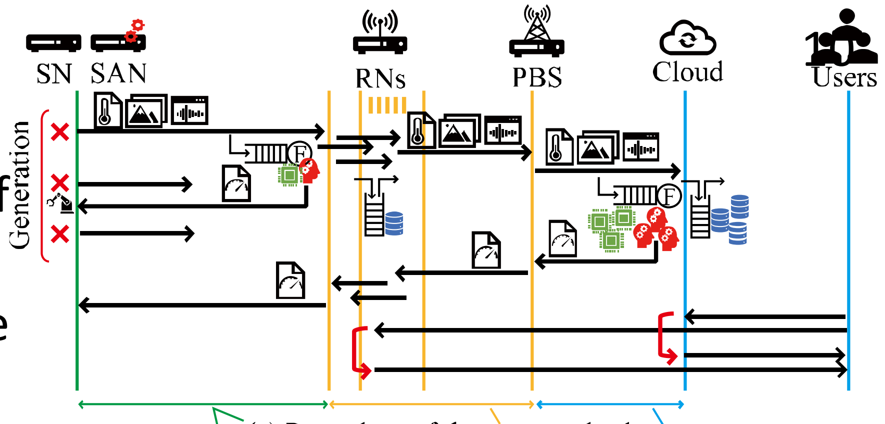


Figure 1. Network model of proposed scheme

- WSANs are distributed and closed-loop feedback control system.
  - WSNs have only a forward channel (uplink) for sensing data.
  - WSANs additionally have a feedback channel (uplink) and a backward channel (downlink) for actuator/actor command data.
- SNs acquire information, then the data are packetized, locally processed, as sensing data, and then they are committed to the network.
- The sensing data are forwarded to PBS, which coordinates the local area, via an edge-side network composed of multiple RNs operating as a mesh.

System description

- Figure 2(a) illustrates the procedure of the proposed scheme.
  - SNs and SANs periodically generate data and send it to the nearest RN.
  - SANs' data is sent to RN, PBS, and cloud servers, and feedback data is sent back to control.



(a) Procedure of the proposed scheme

Figure 2. Procedure of proposed scheme and definition of AoI metrics

- Sensing data are retrieved by users as needed.
  - Users commits data retrieval request (interest) to the network.
  - Data delivery is completed when the nearest node.
- Supposing K SNs/SANs are distributed in an ICWSN or ICWSAN field.
- n th SN/SAN ($n = 1,2,\cdots,N$) sends the sensing data, which is given by

$$\boxed{x_{t+1,n} = ax_{t,n} + bu_{t,n} + w_{t,n} \qquad (1)}$$

- where $x_{t,n}$ is the sensing data via the forward and feedback channels, $u_{t,n}$ is the control data via the backward channel, and $w_{t,n}$ is the (thermal and ambient) noise in the device and channel at time t. a and b are constant values that depend on the environment and device.

AoI definition

- AoI is a time-dependent metric, i.e., delays carry a significant weight.
- As shown in Figure 2(b), four delays are considered:
  - Transmission delay, τ_T, occurs when the transmitter converts it into packet, such as framing, coding, and modulation.
  - Propagation delay, τ_P, is interval for wireless transmission, which is dominated by distance between nodes and wireless conditions.

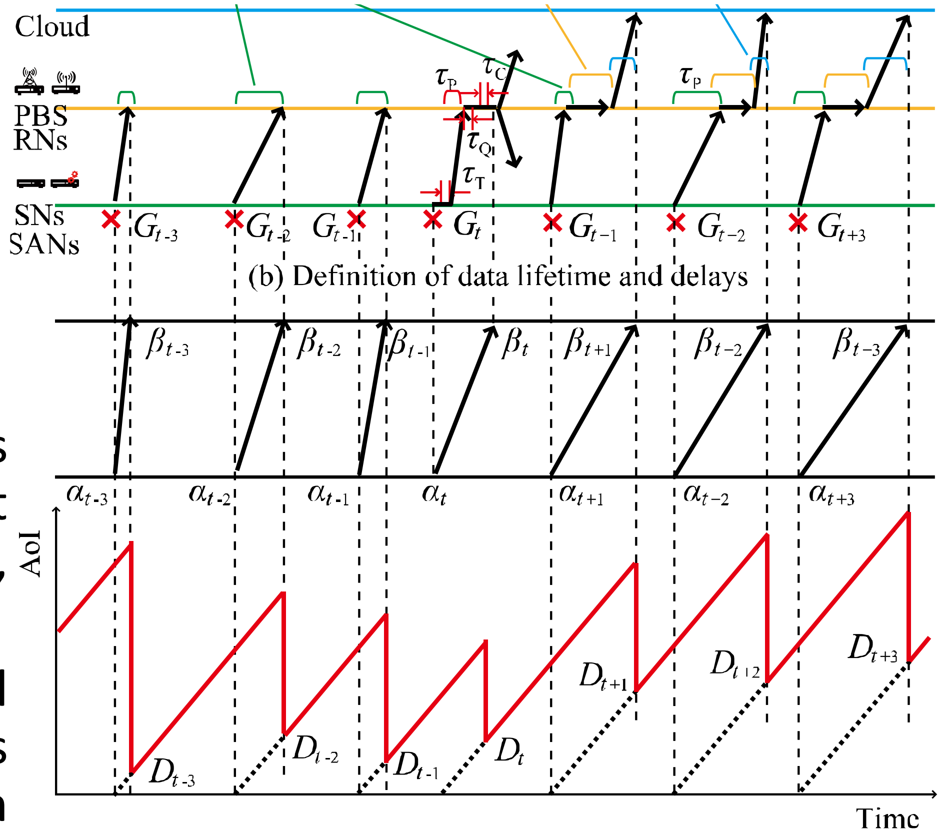


Figure 2. Procedure of proposed scheme and definition of AoI metrics

  - Caching delay, τ_Q, occurs because of network congestion and significant queueing delays due to routing, switching, and protocol processing.
  - Calculation delay, τ_C, arises during computational calculations in functors, depending on the hardware and software implementations.
- As shown in Figure 2(b), let G_t denotes the generative function of the data in any k-th SN/SAN; therefore, the AoI is expressed as shown in Figure 2(c).

AoI definition

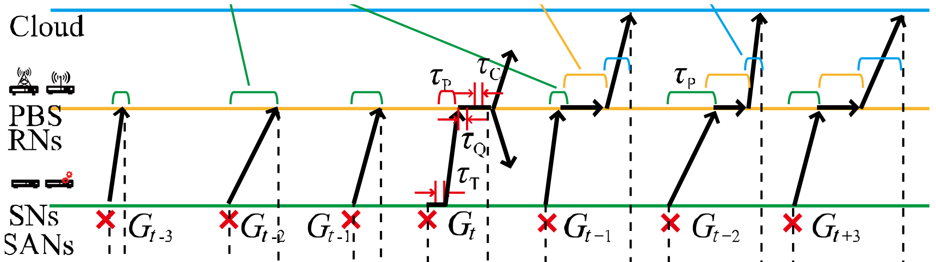
- For any k-th SN/SAN let α_t and β_t denote the timestamp of the data generation and reception at t.
  - We can rewrite $G_t = \alpha_t - \alpha_{t-1}$.
  - Let $\ell(t) \triangleq \beta_t - \alpha_t$ denotes the freshness of the most recently updated data; hence, the AoI at the time t can be expressed as

$$\boxed{\Delta(t) = t - \ell(t) \qquad (2)}$$

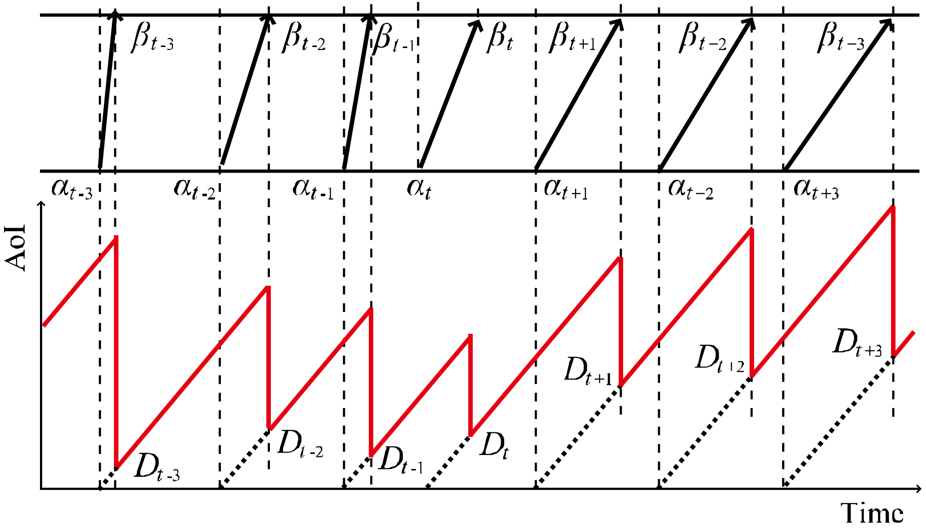
  - $\ell(t)$ can be rewritten based on

$$\boxed{\ell(t) = \tau_{\mathrm{T}} + \tau_{\mathrm{P}} + \tau_{\mathrm{Q}} + \tau_{\mathrm{C}} \qquad (3)}$$

  - For multi-hop, $\ell(t)$ can be calculated multiplying (3) by number of hops.
- In practical aspects, $\ell(t)$ can be calculated from the timestamp recorded in the named data and the current time, under the network nodes are synchronized.



(b) Definition of data lifetime and delays



(c) Definition of age of information (AoI)

Figure 2. Procedure of proposed scheme and definition of AoI metrics

Simulation environment

- Preliminary evaluation of the ICWSN/ICWSAN with AoI is provided based on the platforms[8][14].
- Computer simulations include cache functionality, functors, queues, and wireless communications.
  - SNs were randomly deployed and RNs were placed in a rectangular lattice pattern.
  - Link between SN and RN was microWaves with single-hop and link between RNs was mmWaves.
  - Number of wireless channels was determined based on WLANs (IEEE 802.11 standard).
  - To simplify simulations, delay were set to constant values, data frames were fixed size, and size of cache storage was unlimited.
  - Proposed AoI metric is depending on accurate clock synchronization, but we assume that it is consistently maintained.

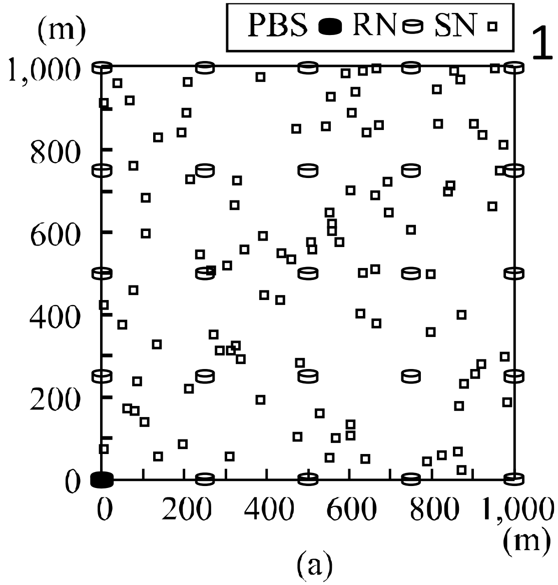


Figure 3. Simulation environment

Table I. Simulation parameters

Terms	Values
Observation field	1 km^2
Number of nodes	N: 10,000 /km^2, K: 25
Number of channels	24 (microWaves), 108 (mmWaves)
Coverage range	200 m
Delays	τ_{T}: 300 ms, τ_{P}: 500 ms, τ_{Q}: 100 ms, τ_{C}: 1,000 ms

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

[14] 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.

Simulation results

- Figure 4 shows CDF of number of SNs per RN and it was unbalanced.
  - Minimum value was 117.
  - Maximum value was 718.
  - Average value was 400.
  - Median value was 322.
- For simplicity, we assumed RN contains 400 SNs.
- Figure 5 (a) and (b) shows channel occupancy rate and average number of lost data versus interval between data generations and number of interference nodes.
  - Given an interval of 30 s or longer and no interference nodes, the system can work without packet loss or buffer overflow.
  - Even with an interference node present (up to four neighboring cells), the results showed that the system worked properly with a 60-s interval, whereas it was completely ineffective with a 30-s interval.

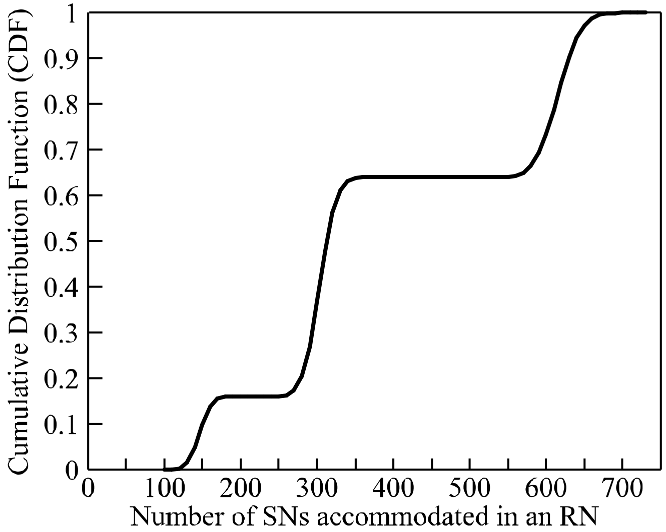
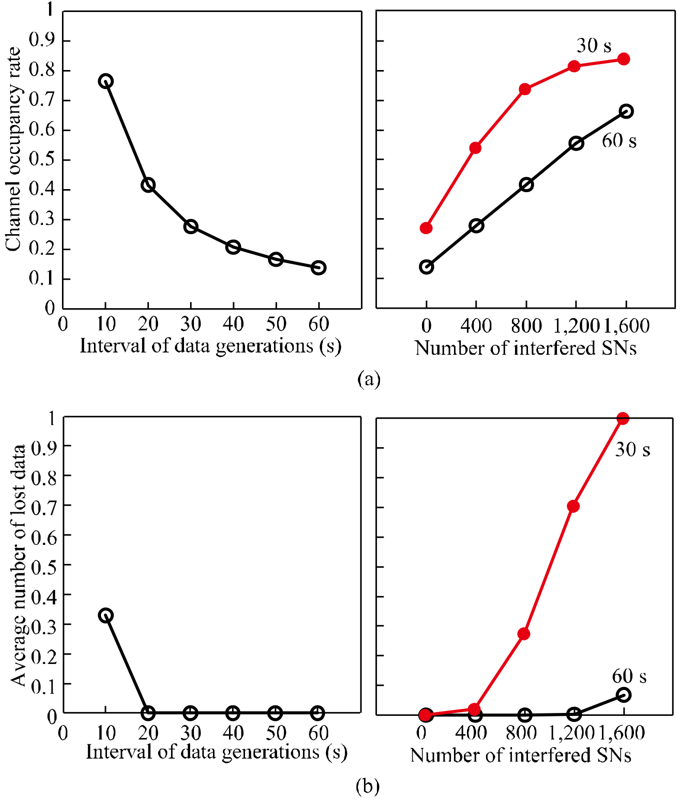


Figure 4. Simulation results



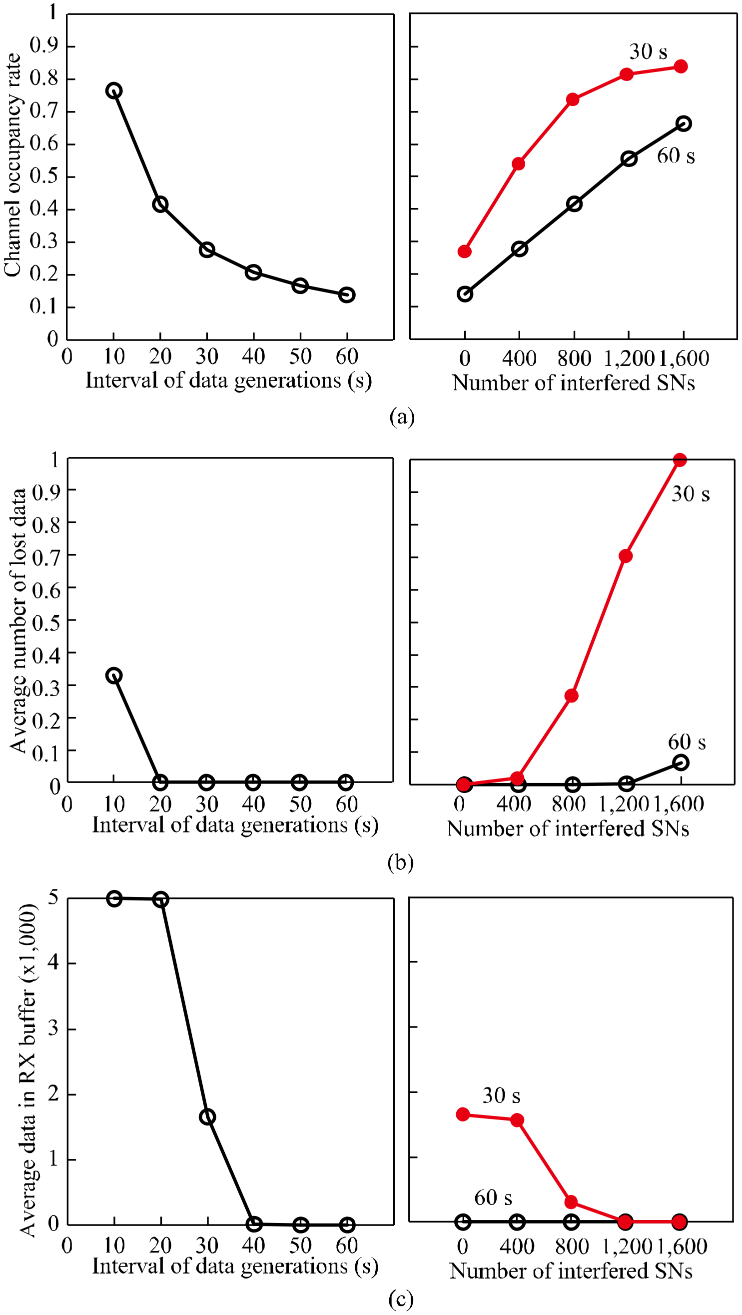
(a)

(b)

Figure 5. Simulation results

Simulation results

- Figure 5 (c) shows that the average data size accumulated in the receiver buffer versus interval between data generations and number of interference nodes.
  - The buffer can be improved when the amount of generated data increases.
  - The interval and interfered nodes were increased, because the buffer is overflowed and then the data cannot reach the receiver node.

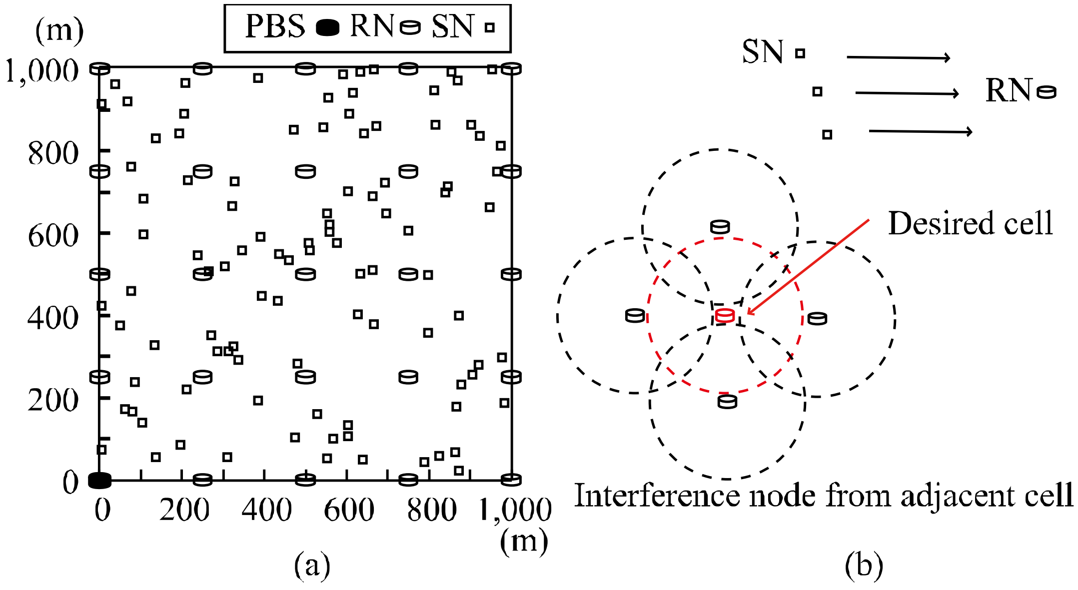


(a)

(b)

(c)

Figure 5. Simulation results



(a)

(b)

Figure 3. Simulation environment

Simulation results

- Figure 6 shows the CDF versus freshness of the most recently updated data.
- $\ell(t)$ is a numerical example directly related to AoI.
  - Under ideal conditions, delay would be 800 ms as represented by the arrow.

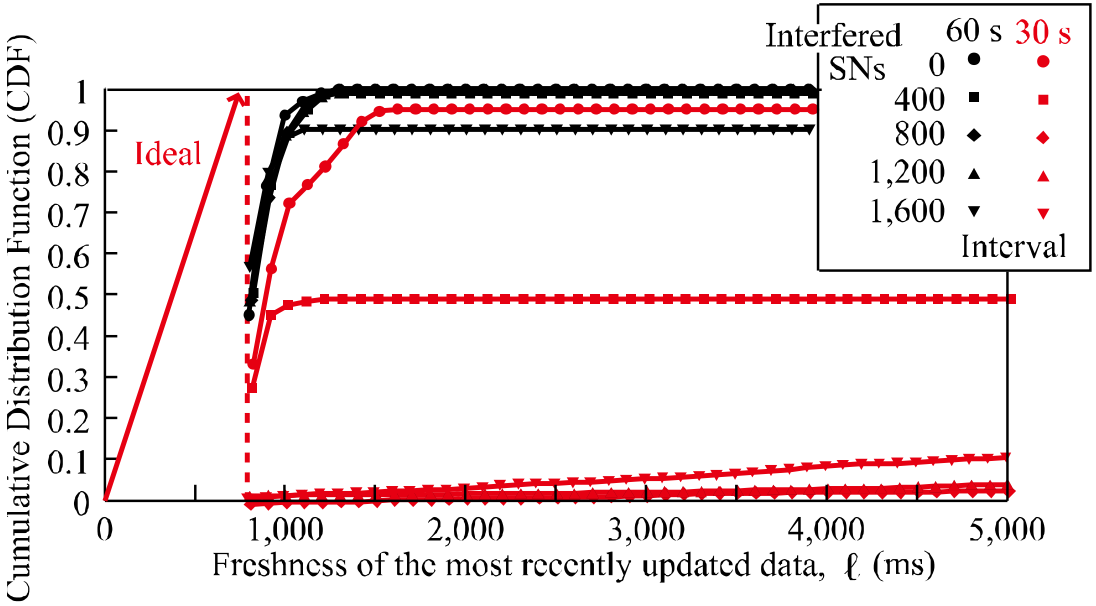


Figure 6. Simulation results

  - Due to wireless channel, the receiver-side buffer, and interference from neighbor nodes, the arrival time, β, was delayed, resulting in a larger $\ell(t)$.
  - For 60-s intervals, the data arrives within 1,500 ms, even with interference from neighbors.

- Based on these numerical results, the constant parameters should be determined to ensure that AoI-based data freshness is appropriately performed depending on the network scale, which is a future study and ongoing work.

Conclusion and future work

- This paper proposed to introduce an AoI-based metric to the ICWSAN system as an essential delay indicator for delay-sensitive applications and provided a preliminary evaluation.
- As a future work, more detailed simulations and evaluations should be conducted.

Thank you for your attention!

• This work was partly supported by JSPS KAKENHI Grant Number JP25K15104.