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Network-Performance Evaluation for Millimeter-Wave Information-Centric Wireless-Sensor-Network Ecosystem in Actual City

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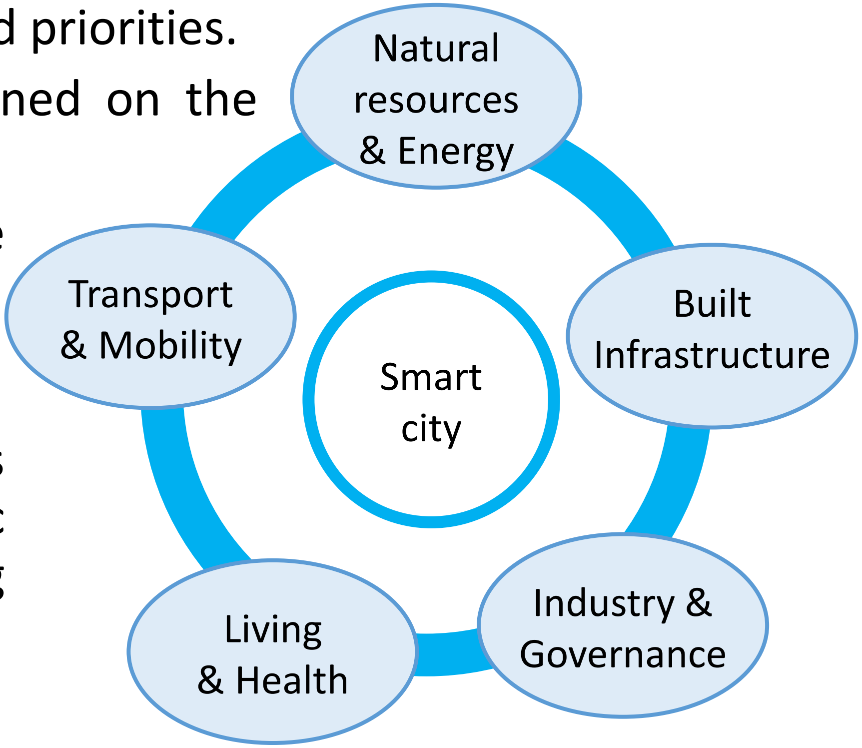
Biography

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

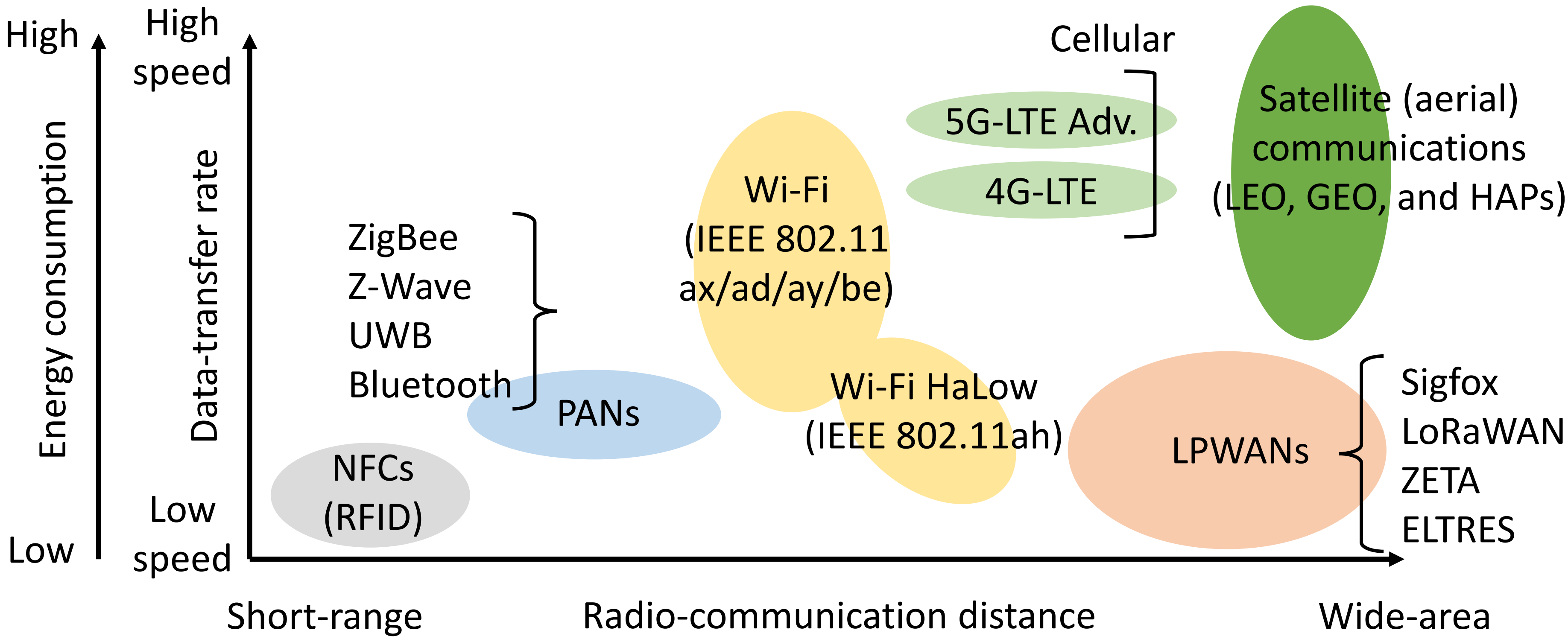
- A wireless sensor network (WSN) is an essential technology supporting smart-city application services.
- In these applications, sensor nodes (SNs) are heterogeneously interconnected to collect and distribute data, e.g., real-time streaming and high-capacity data.
  - The data include various demands and priorities.
  - These transmission method is designed on the basis of several protocols.
- These should be accommodated in the same ecosystem [1].



- Millimeter-wave wireless communications (mmWaves) [2] and information-centric networking (ICN) [3][4] have been gaining attention.

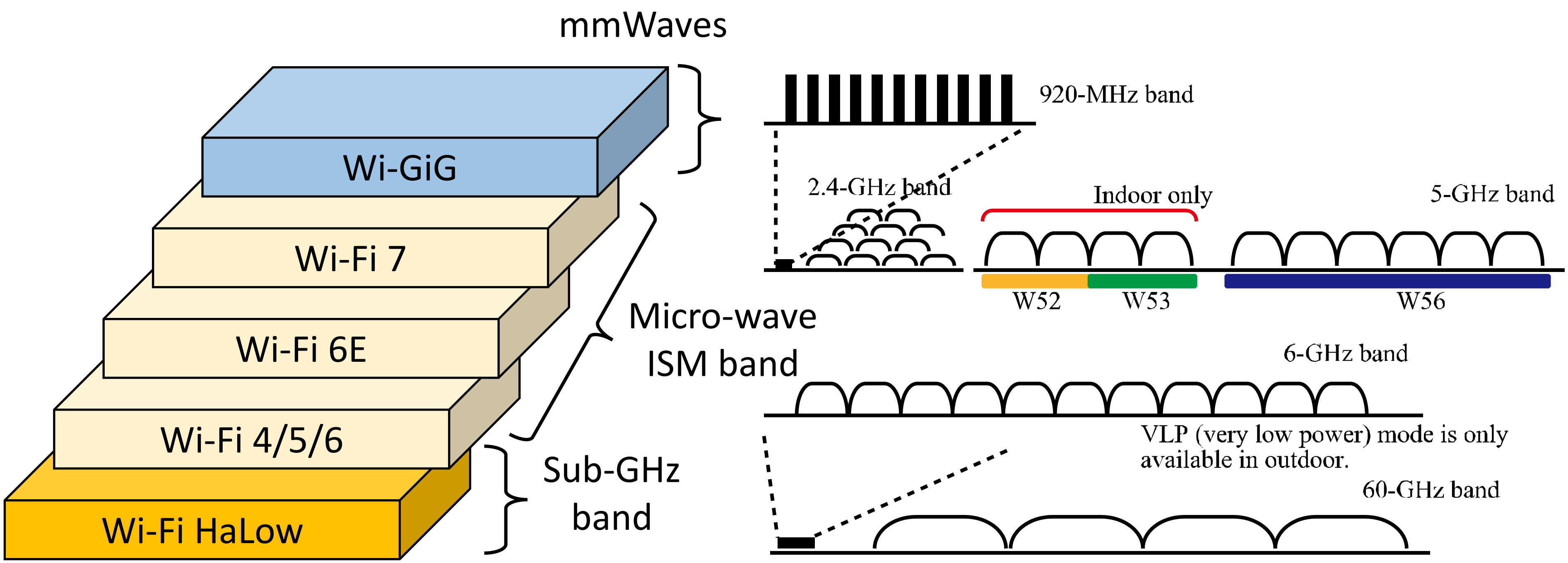
[1] P. Mishra, et al., “6G-IoT framework for sustainable smart city: Vision and challenges,” *IEEE Consumer Electronics Mag.*, pp. 1–8, Sept. 2023.
[2] K. Aldubaikhy, et al., “MmWave IEEE 802.11ay for 5G fixed wireless access,” *IEEE Wireless Communications*, vol. 27, no. 2, pp. 88–95, Apr. 2020.
[3] B. Ahlgren, et al., “A survey of information-centric networking,” *IEEE Communications Mag.*, vol. 50, no. 7, pp. 26–36, July 2012.
[4] L. C. M., et al., “Application areas of information-centric networking: State-of-the-art and challenges,” *IEEE Access*, vol. 10, pp. 122431–122446, Nov. 2022.

Wireless Communications for Smart-city Deployment



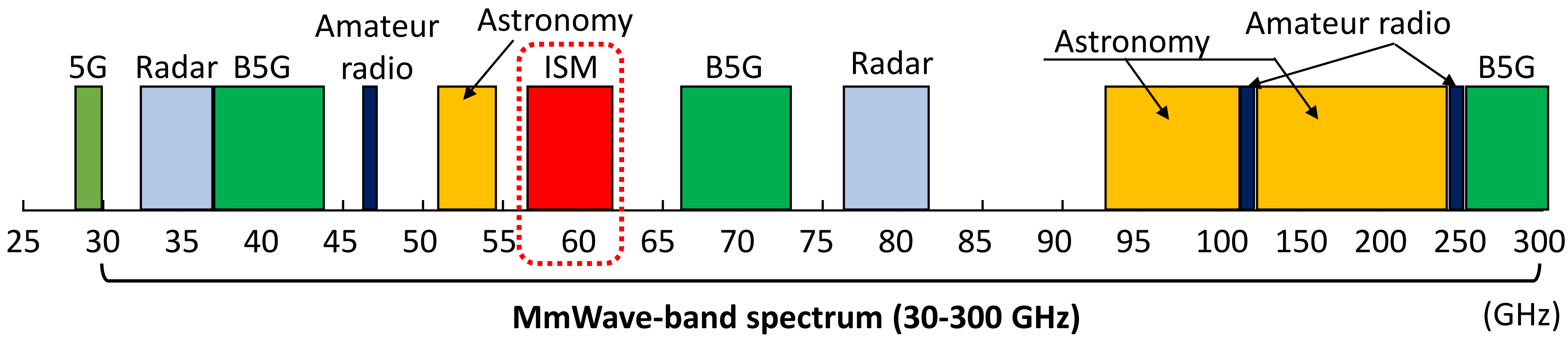
- Cellular and satellite telecommunication are the de facto wireless system for smart-city applications; however, it is costly to deploy.
- Low-power wide-area networks (LPWANs) are the primary solutions; however, they can only transmit a few small data packets within 100-Hz bandwidth below the 1-GHz band.
- Short-range personal area networks (PANs) based on IEEE 802.15 standards are traditionally used for WSNs, but can be used as a network inside a regional area.

Wireless Local Area Network (LAN) (Wi-Fi)



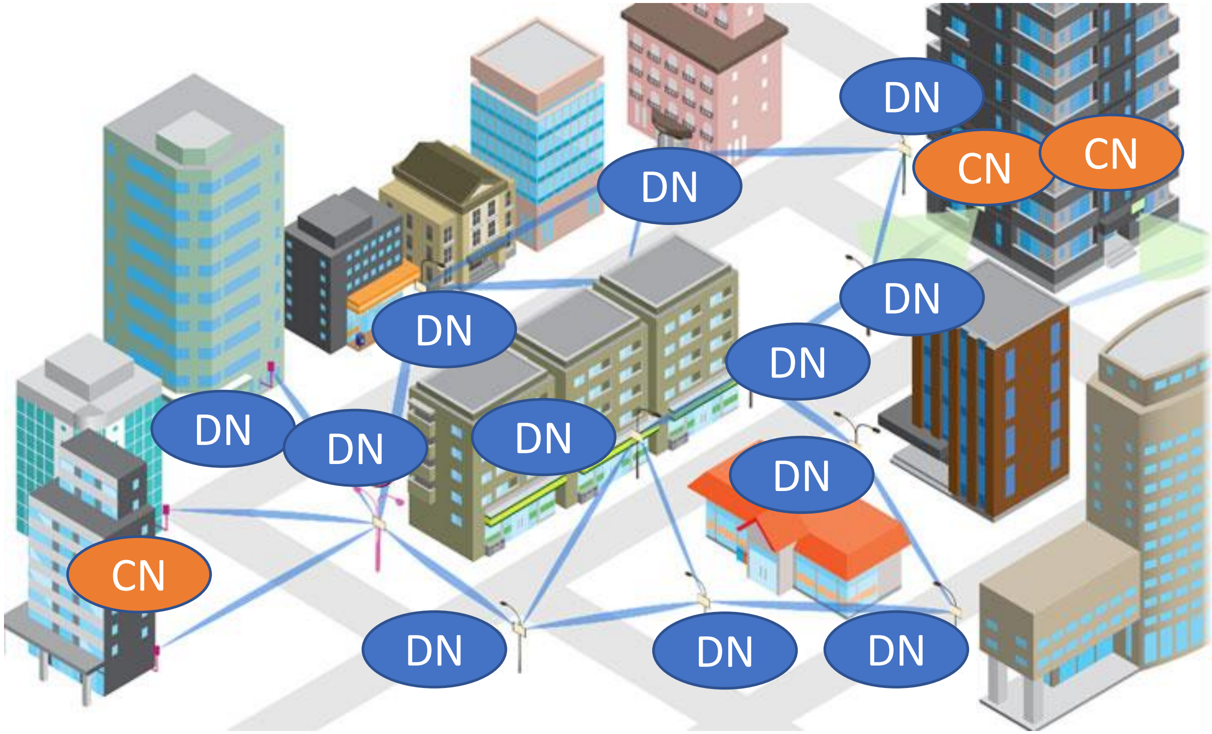
- Another global communication system, wireless local area networks (WLANs) based on IEEE 802.11 standards, known as Wi-Fi.
- WLANs can provide extensive and various connectivity for computers, tablets, smartphones, and IoT devices.
- Wi-Fi-based networks are the optimal candidate, because they have several advantages: low-cost wireless modules are readily available, they can be based on IP networks, and the multiple radio-frequency bands can include unlicensed bands, such as 920 MHz and 2.4, 5, 6, and 60 GHz, without regulations.

MmWave-wave Wireless Communications (mmWaves)



- Millimeter-wave wireless communications (mmWaves) have been recognized as a global frontier in future mobile technologies, enabling multi-gigabit data transfer over vast spectrums.
- MmWaves have been used as an alternative to backhaul, both short-range and high-capacity indoor communications, or radar and astronomy.
- Compared with the radio-frequency bands that are currently widely used, the extra attenuations for the link budget of mmWaves.
  - Rain, oxygen, and hydrophilic materials (e.g., trees, leaves, and humans) must be considered.
  - 60-GHz radio waves are particularly affected by the rain and oxygen.
- Related studies include the applicability of mmWaves for outdoor applications to provide several hundred meters of coverage.

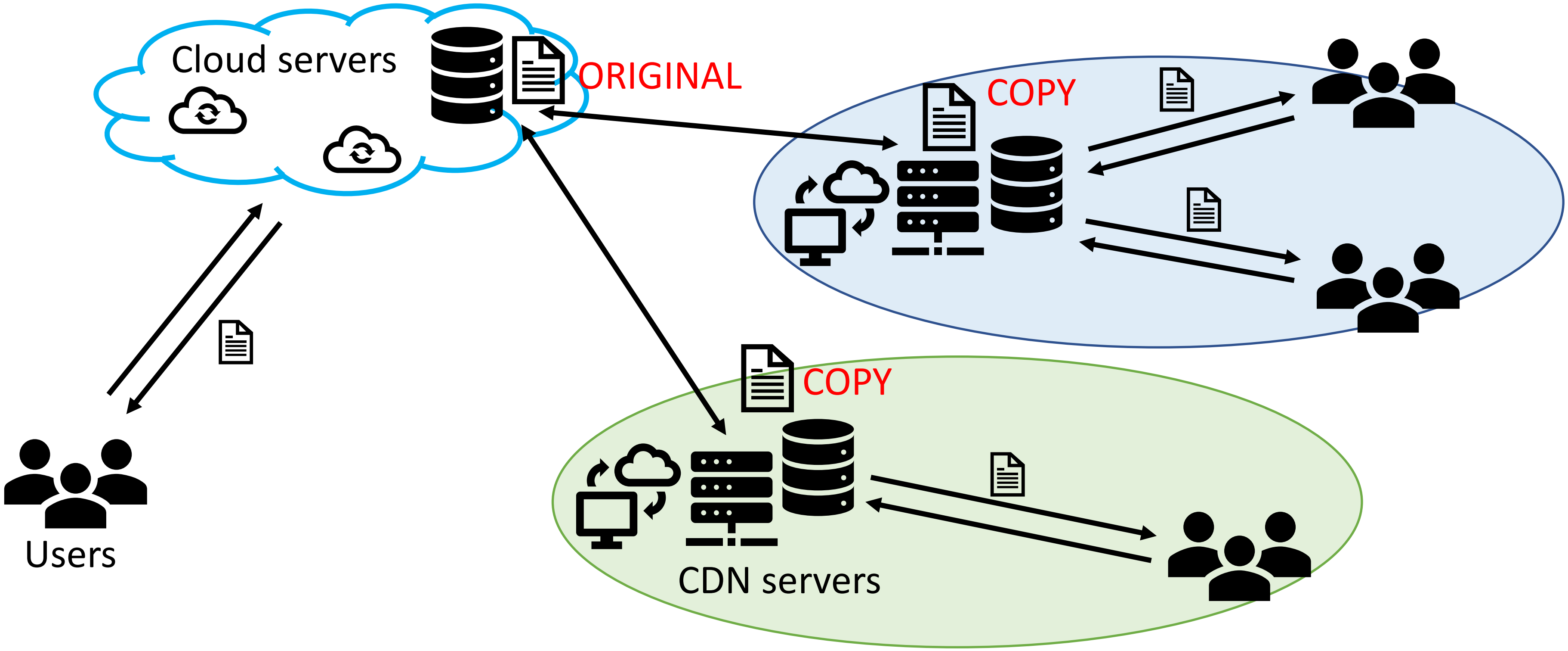
Terragraph



- IEEE 802.11ay supports mesh networks, which can provide a cost-efficient broadband wireless solution to replace fiber optical networks in city areas.
- As a commercial product, Meta (Facebook) offer Terragraph [16].
- To the best of our knowledge, there have been few experiments regarding mmWave long-distance data transmissions; hence, we believe that the contribution of this paper is valuable.

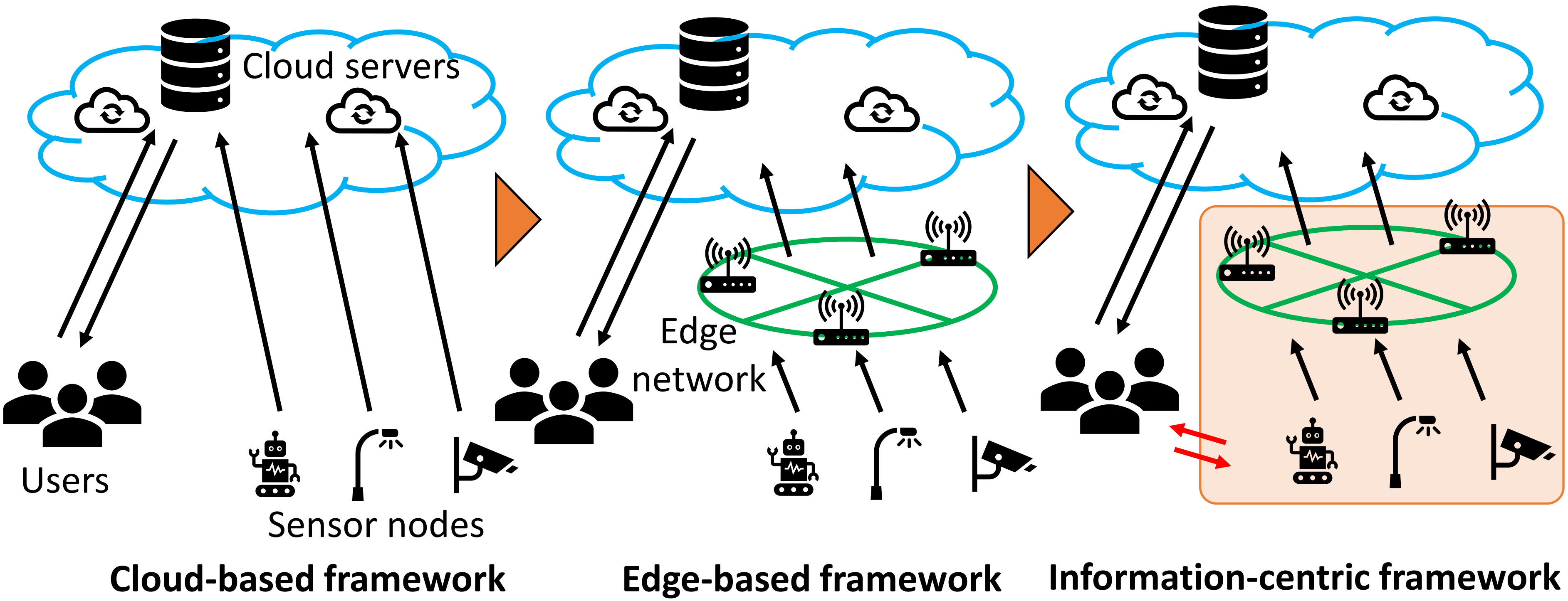
[16] Terragraph, https://terragraph.com/ (retrieved: Jan. 2025).

Evolution of Networking Technology



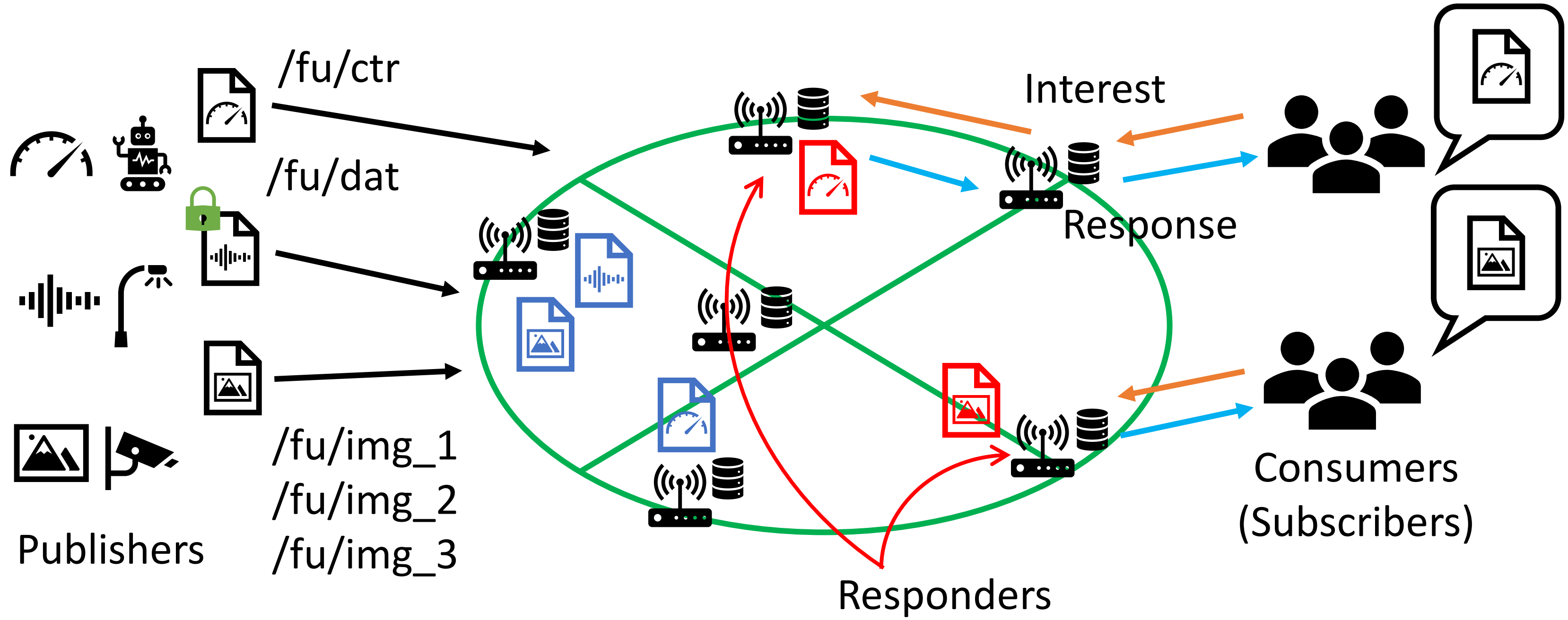
- In the current network system, data are gathered and stored on the cloud servers, and the users find and obtain them from the central locations.
  - With the growth of data consumers, network bandwidth will be too tight.
- The content delivery network (CDN) technique is widely used to improve network 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.

ICN Meets IoT Framework



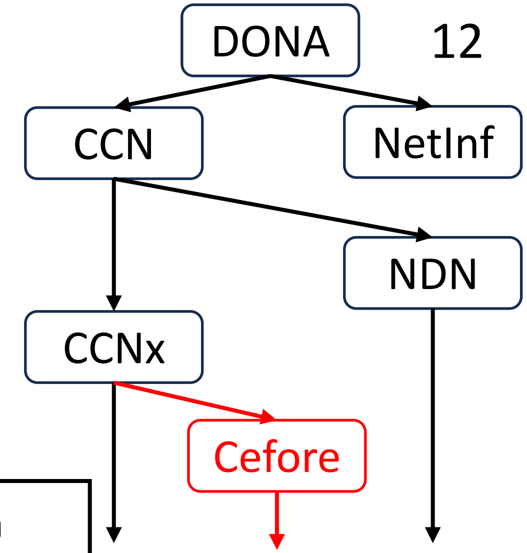
- Future network architecture shifts the focus from host locations to data.
- ICN is a data-oriented network protocol that focuses on content delivery.
  - The search engines (or domain name systems) reply with the IP address for the keyword, and the users obtain the data based on the address.
  - Peer-to-peer (P2P) networks find the node with the data, and the user directly communicates with the node based on the address.

Information-Centric Wireless Sensor Network (ICWSN)



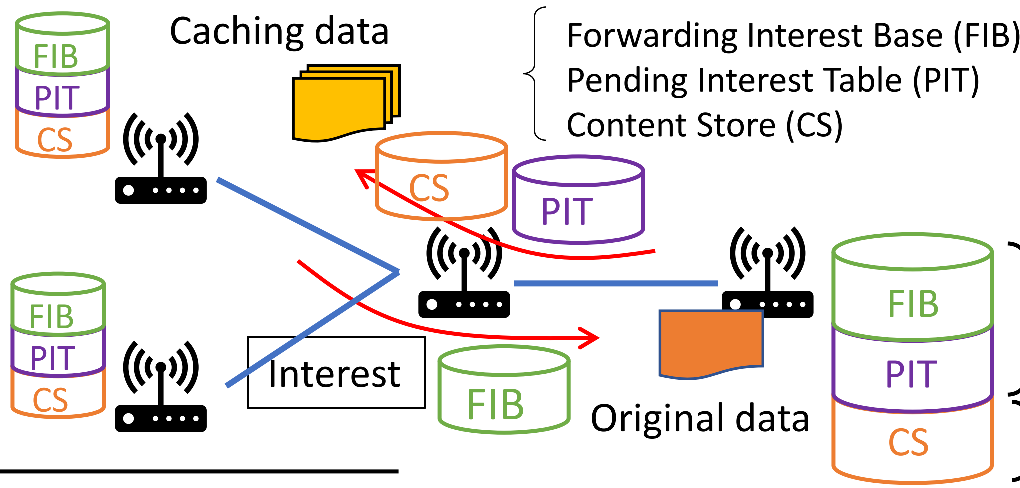
- The data are named instead of an address, enabling end-users to discover and obtain the data via names, resulting in network abstraction.
- The named data are handled separately by individual content units, i.e., they can be self-certified and encrypted.
  - ICN scheme contributes to improved security, in-network caching schemes are also available, i.e., the data are copied and stored in cache memories on network nodes to facilitate further data retrieval.
  - Peer-to-peer (P2P) networks find the node with the data, and the user directly communicates with the node based on the address.

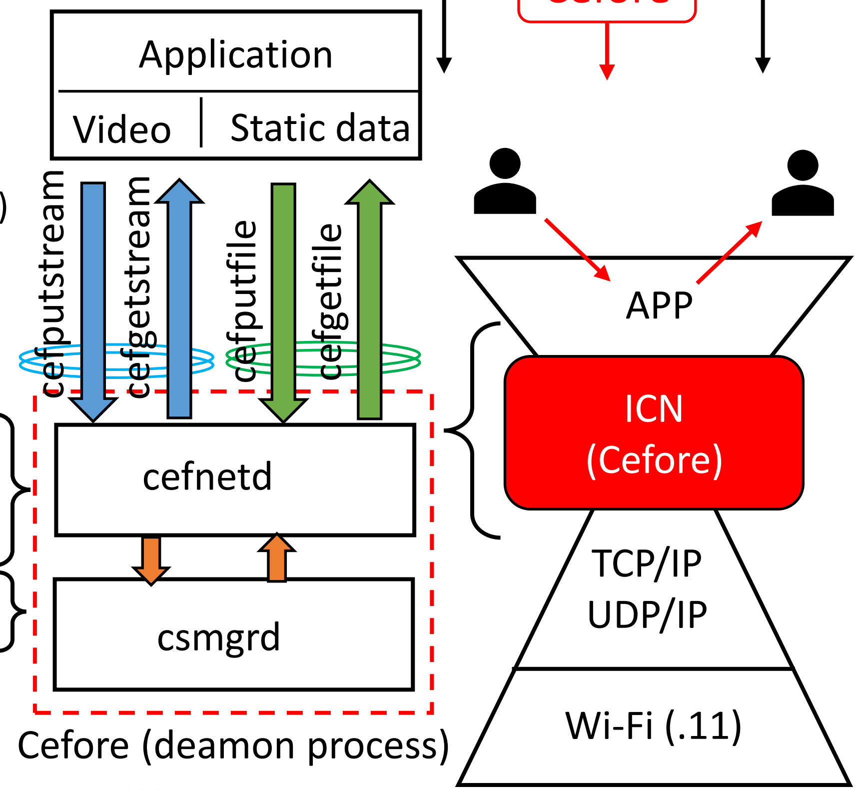
ICN Platform: Cefore



- In our prototype mmICWSN [5][6], we used Cefore [17] for the middleware of the ICN platform.
- Cefore is an open-source CCNx-based ICN platform available on Linux (Ubuntu).

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





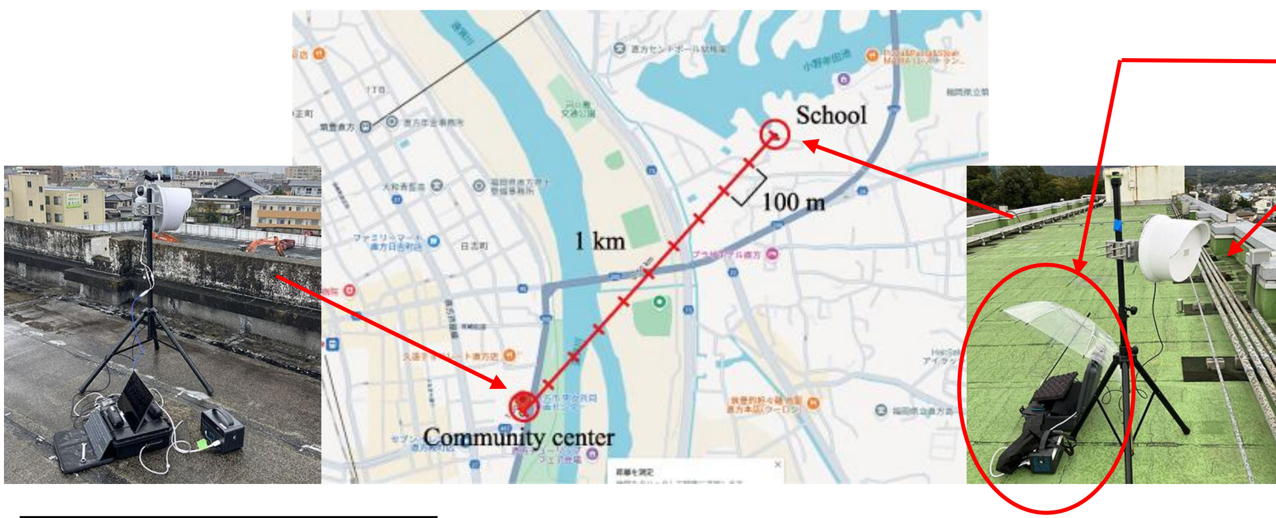
[5] S. Mori, "Zero-touch-design information-centric wireless sensor networking with availability assurance," *International J. Advances in Networks and Services*, vol. 16, no. 3&4, pp. 63–74, Dec. 2023.

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

[17] Cefore, https://cefore.net/ (retrieved: Jan. 2025)

Experimental Environment

- The prototype mmICWSN was implemented not limited to a specific application service but designed on the basis of a reliable and zero-touch design [7].
- The device was designed to be waterproof since it would be placed in outdoor.
- The devices were deployed at a community center and school in Nogata City (Fukuoka, Japan).
  - Community center and school are three-story buildings, and they were placed on the rooftops.



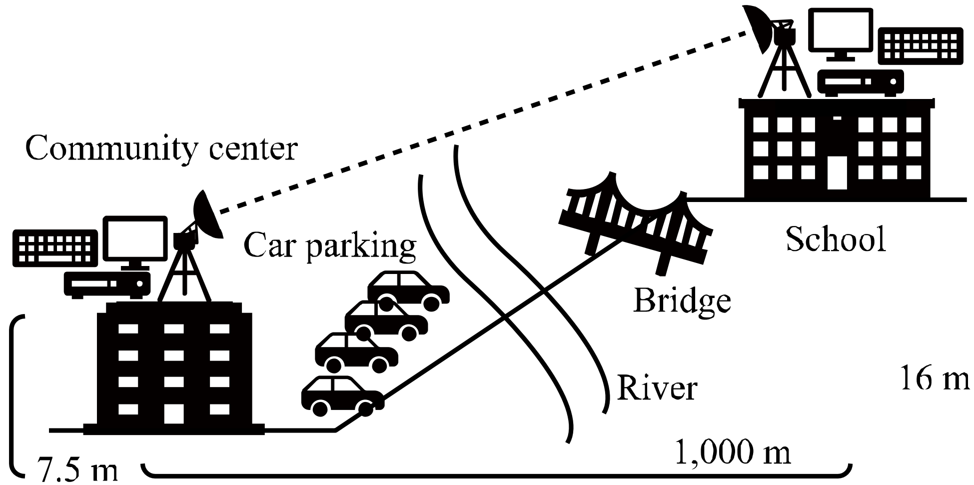
Specification of Terragraph device

Terms	Values
Radio frequency	58.32 GHz with 2.16 GHz
Transmission power	56 dBm (EIRP)
Antenna	Phased array antenna with dish Gain: 40 dBi Scan range: ±3°, Beam width: ±1°
Dimensions	355 × 355 × 315 mm
Weight	3 kg

[7] 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.

Experimental Environment

- Across the wireless link, there are a river, road, bridge, and car park.
  - The river is the Onga River and the riverside area is well maintained and covered with grass and aquatic plants.
  - During the experiment, the river surface was flat and calm, with no significant waves.



  - Kanroku Bridge crosses the river and is connected to the main national road.
  - Nogata City is an inter and suburban city between large cities (e.g., Fukuoka City and Kitakyushu City), but the amount of traffic is not dense.
  - The riverside area in front of the community center is used as a car park, and several dozen cars were parked there.
  - In accordance with the three-dimensional map provided by the National Geographical Institute, their altitudes are respectively 7.5 and 16 m, and straight-line distance is 1 km.

- The factors affecting mmWave propagation were not observed.

Field Views of Experimental Field

Field views at the community center

Field views at the school

- The mmICWSN node devices were connected to the BeMap MLTG-CN/LR [19] as the mmWave Terragraph device.
  - These devices communicated with each other, and the coverage range was up to 1 km, according to the catalog specifications.
  - The Modulation and Coding Scheme (MCS) index was automatically set as 9.
- The weather was cloudy during the experiment, i.e., the possibility of rainfall attenuation to degrade the mmWave propagation could be ignored.

Specification of Terragraph device

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Weight	3 kg

[19] BeMap, https://www.bemap.co.jp/ (retrieved: Jan. 2025).

Field Views of Experimental Field

- The parameter settings regarding adaptive rate control in the IEEE 802.11ay.
  - IEEE 802.11ay-based Wi-Fi systems uses the pre-defined as MCS settings, including modulation method, code rate, and repetition code

MCS settings in single carrier physical mode

Index	Modulation method	Code rate	Repetition	Data rate (Mbit/s)
1	BPSK	1/2	2	385
2	BPSK	1/2	1	770
3	BPSK	5/8	1	963
4	BPSK	3/4	1	1,155
5	BPSK	13/16	1	1,251
6	QPSK	1/2	1	1,540
7	QPSK	5/8	1	1,925
8	QPSK	3/4	1	2,310
9	QPSK	13/16	1	2,503
10	16-QAM	1/2	1	3,080
11	16-QAM	5/8	1	3,850
12	16-QAM	3/4	1	4,620

- Photo was taken behind the dish antenna on the school rooftop toward the community center.
  - The community center is located at the red marking, where the opposite node was placed.
  - The line of sight between the transmitter- and receiver-side nodes can be clearly maintained.

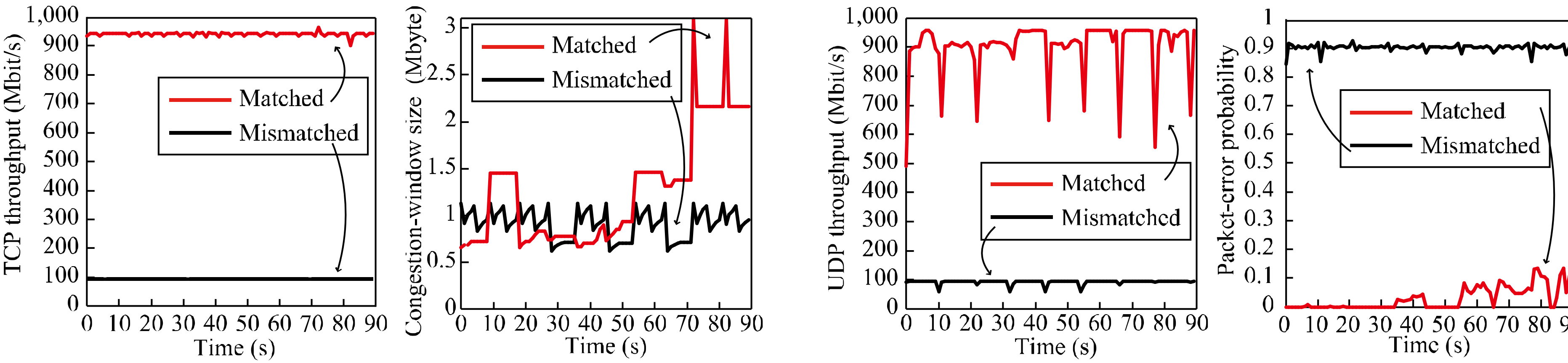
Experimental Environment

Physical-layer information in experiment

Terms	Antennas are matched	Antennas are mis-matched
Radio channel	Ch 2 (60.48 GHz with 2.16 GHz)	
RSSI	-64 dBm	-62–63 dBm
MCS settings	8–9	6–9
Beam index	30 / 30	30 / 5

- Experiment was conducted for different scenarios:
  - Antennas were matched: Both elevation and azimuth angles were appropriately adjusted.
  - Antennas were mismatched: They were offset.
- The status information of the physical layer for these scenarios is summarized.
  - Antenna's front space is divided into a grid pattern in terms of elevation- and azimuth- angles. Each sub-region is assigned a beamforming index.
  - The most central beam direction on the antenna surface is when the beamforming index is 30.
- Network performance:
  - TCP and UDP throughput were measured using iPerf3.
  - We measured TCP/UDP throughput at every 1 s interval for 90 s.
  - The CUBIC algorithm were used in TCP evaluation.
  - The nodes in the community center and school were assigned as server and client nodes.
- ICN performance:
  - We measured the ICN throughput using Cefore.

Experimental Results



Throughput **CW size**

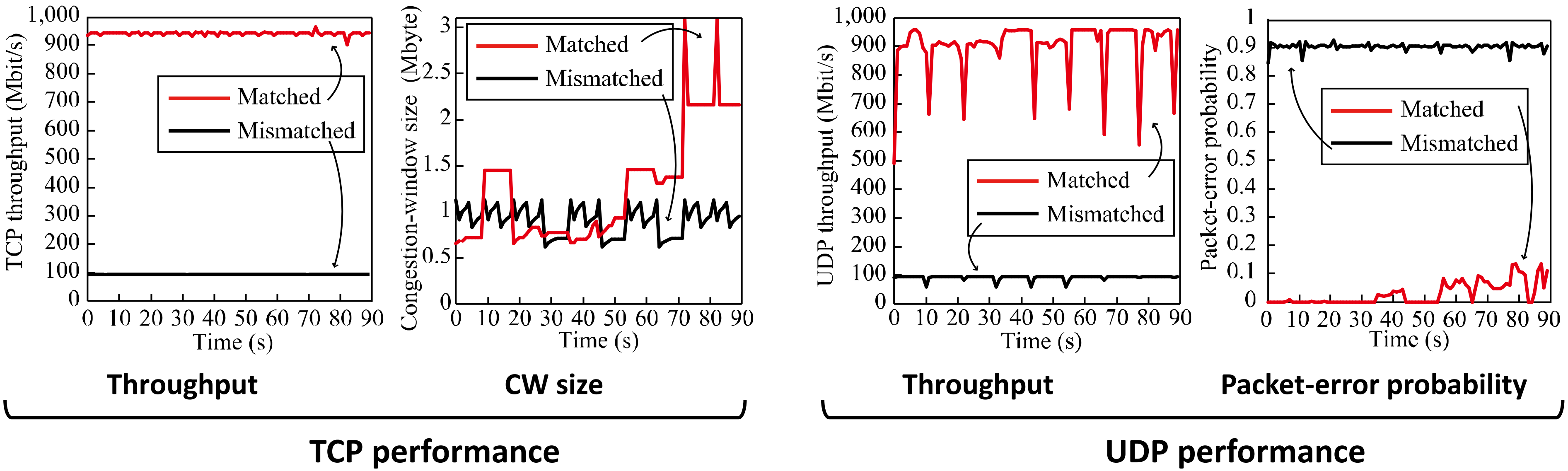
TCP performance

Throughput **Packet-error probability**

UDP performance

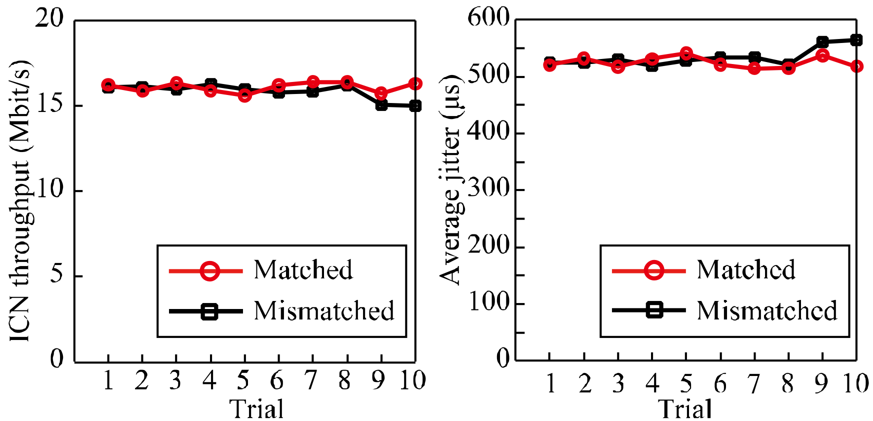
- TCP performance:
  - Average throughput was 941 and 94.4 Mbit/s for when the antennas were matched and mismatched, respectively.
  - The antenna is a parabolic dish type; thus, even a few degrees of angle misalignment can cause significant throughput degradation.
  - For TCP congestion control, the average congestion-window size was 1.26 and 0.967 Mbytes; hence, there was a 39.3% difference.
  - In the curve when the antennas were matched, several attempts were made to increase the congestion-window size.

Experimental Results



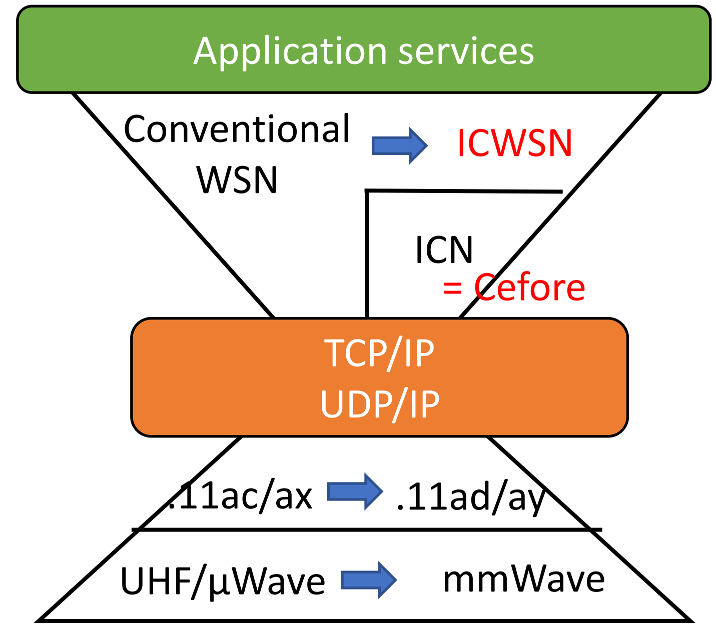
- UDP performance:
  - Average throughput was 902 and 93.3 Mbit/s for when the antennas were matched and mismatched, respectively.
  - In the curve when the antennas were matched, there were regions where UDP throughput temporarily decreased.
    - This reason is that automatic retransmission requests and forwarding-error-control mechanisms are omitted.
    - The results of TCP throughput indicate no degradation because the congestion-control mechanism is available and useful works.
  - Packet-error probability for UDP transfer; the averages were 0.0294 and 0.903 for the matched and mismatched scenarios, respectively.

Experimental Results



Throughput **Jitter**

ICN performance



- ICN performance:
  - Average throughput was 16.1 and 15.8 Mbit/s for when the antennas were matched and mismatched, respectively.
  - The ICN throughput was significantly smaller than that of TCP/UDP because Cefore has a bottleneck in terms of implementations and structures.
    - If the transmission bandwidth is set as the maximum value, the failure probability of data registration, storage, and transfer becomes worse.
  - Average jitter was 525 and 534 µs for the two scenarios, respectively.
- The performance of TCP/UDP/IP layers was not affected by that of the ICN layer.
- We could obtain sufficient network performance for mmICWSN in an actual city.

Conclusion and Future Work

- Contribution:
  - We evaluated the feasibility of the network performance in the TCP, UDP, and ICN protocols with mmICWSN.
  - From the experimental results, we found that it was necessary to improve the ICN throughput by modifying the Cefore settings, and the antenna placement for mmWaves was sensitive to a few degrees of angle.
  - Through the demonstration of the mmWaves experiment, the developed system could be applicable to long-distance wireless transmission in an actual city.
- Future work:
  - We plan to deploy mmICWSN for practical smart-city applications, such as smart agriculture.
  - *In detail, we will develop a new ecosystem that supports an on-demand and real-time video and image forwarding platform for a common demand for smart-agriculture applications.*

Shintaro Mori, "Concept of Ecosystem for Smart Agriculture: Milimeter-Wave Information-Centric Wireless Visual Sensor Network," *Proc. IARIA Congress 2025*, Venice, Italy, July 2025. (accepted)

Thank you for your attention.

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