Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: [Wi-SUN: An IoT network that has been successfully commercialized on a large scale by IEEE 802.15.4]
Date Submitted: 15 January 2025
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Abstract: The Wireless Smart Utility Network (Wi-SUN) system is an IoT network that has been successfully commercialized on a large scale based on IEEE 802.15.4. This presentation introduces an overview of the Wi-SUN system, its basic characteristics, and future developments. A part of this contribution is supported by National Institute of Information and Communications, Japan Technology (No. JPJ012368C05101) and MIC/Japan (JPJ000254).”

Purpose:

Wi-SUN: An IoT network that has been successfully commercialized on a large scale by IEEE 802.15.4

Jan. 15, 2024

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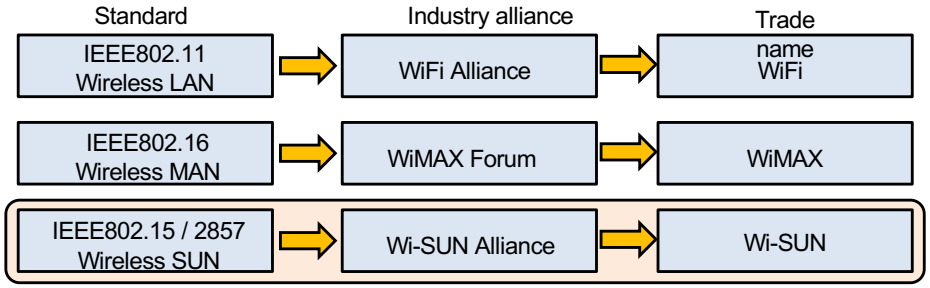
Executive research director, NICT

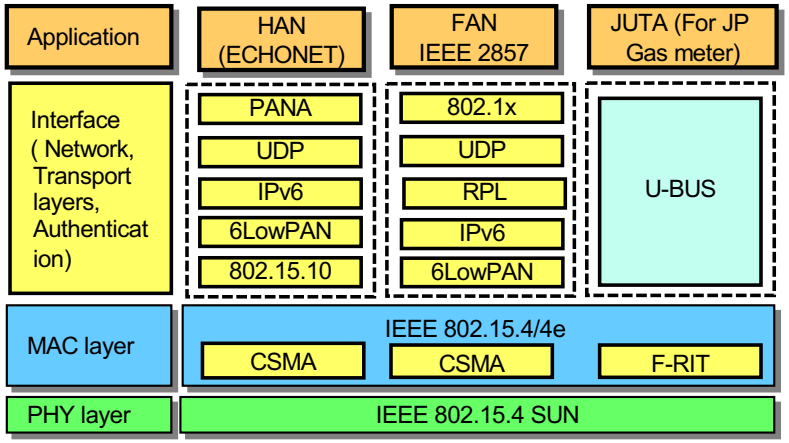
Chairman of the Board of Directors, Wi-SUN alliance

Vice Chair, IEEE 802.15.4g/15.4m/15.4aa/15.4ad and IEEE 2857

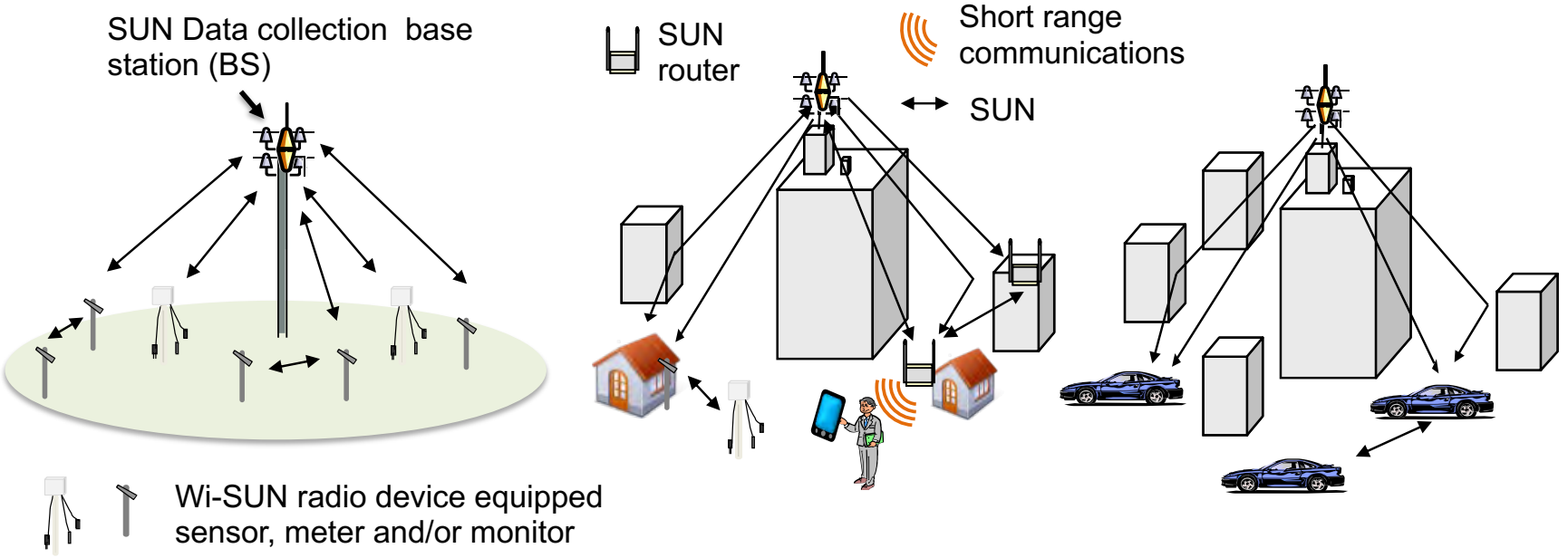
Wireless Smart Utility Network (Wi-SUN)

- Definition of SUN (From 802.15.4-2024)
  - Enable multiple applications to operate over shared network resources, providing monitoring and control of a utility system.
  - Devices are designed to operate in very large-scale, low-power wireless applications and often require using the maximum transmit power available under applicable regulations, in order to provide long-range, point-to-point connections.
  - Required to cover geographically widespread areas containing a large number of outdoor devices.
  - Devices typically employ mesh or peer-to-peer multihop techniques to communicate with an access point.
- Mainly used in the smart metering systems but not limited to
  - Smart city, Street factory, V2X, Medical agriculture…
- Wi-SUN alliance, established in 2012, certified IEEE 802.15.4 SUN-based devices worldwide
- Wi-SUN alliance certified three brands of products based on IEEE 802.15.4





Expected use cases



(a) Wide area open space communication

(b) Wide area urban area communication

(c) Wide area mobile communication

H. Harada, K. Mizutani, J. Fujiwara, K. Mochizuki, K. Obata, and R. Okumura, "IEEE 802.15.4g based Wi-SUN Communication Systems," IEICE Transactions on Communications, E100-B, No. 07, pp. 1032–1043, Jul. 2017.

PHY parameters focusing on Wi-SUN

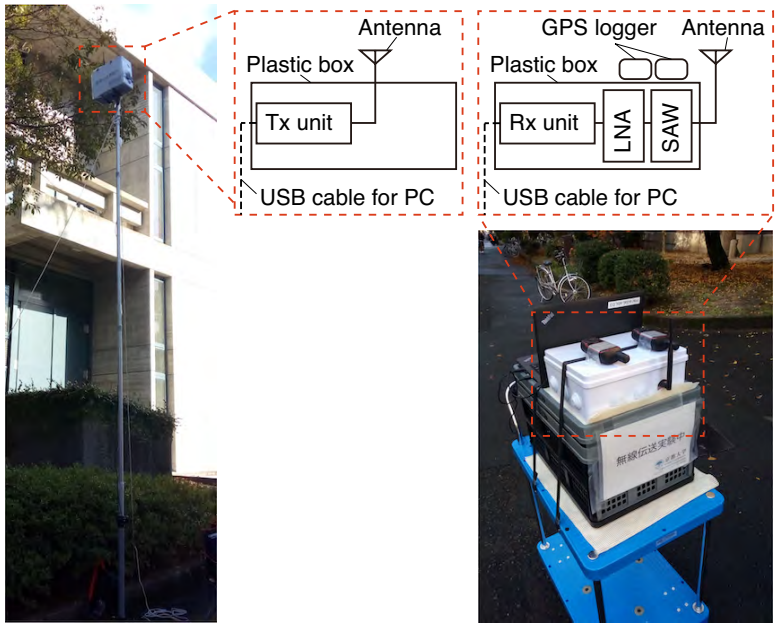
FSK

Parameter	mode #1	mode #2	mode #3	mode #6	mode #7	mode #8	mode #9	mode #10
Data rate (kb/s)	50	100	200	150	300	300	400	600
Modulation	2-FSK	2-FSK	2-FSK	2-FSK	2-FSK	2-FSK	2-FSK	2-FSK
Modulation index	1.0	1.0	1.0	0.5	0.5	0.5	0.5	0.4
Channel spacing (KHz)	200	400	600	400	400	600	1000	1000

OFDM

		Option1	Option2	Option3	Option4
Nominal Bandwidth		1094 kHz	552 kHz	281 kHz	156 kHz
Channel spacing		1200 kHz	800 kHz	400 kHz	200 kHz
Subcarrier spacing		31.25/3 kHz			
DFT size		128	64	32	16
Primary modulation scheme		BPSK(MCS 0-1), QPSK(MCS 2-4), 16QAM(MCS5-6)			
Coding Scheme and rate		Convolutional code (Constraint length: 7) Coding rate1/2 (MCS 0-3, 5), 3/4 (MCS 4,6)			
Spreading factor		4 (MCS 0), 2 (MCS1-2), 1(MCS 3-6)			
Data rate for PSDU (kb/s)	MCS 0	100	50	25	12.5
	MCS 1	200	100	50	25
	MCS 2	400	200	100	50
	MCS 3	800	400	200	100
	MCS 4	1200	600	300	150
	MCS 5	1600	800	400	200

Field Experiment with FSK

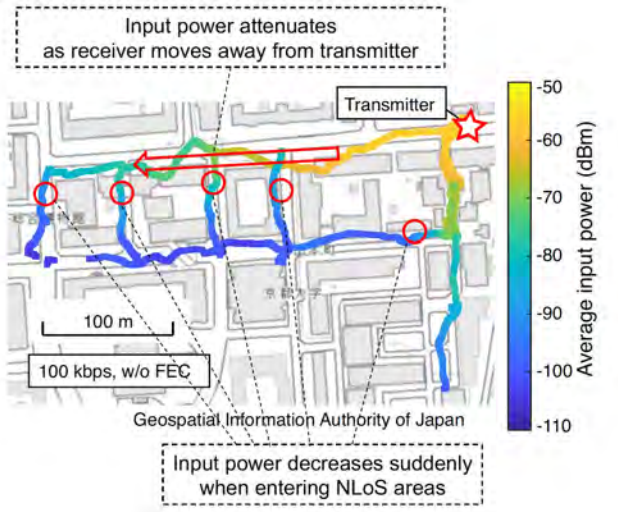


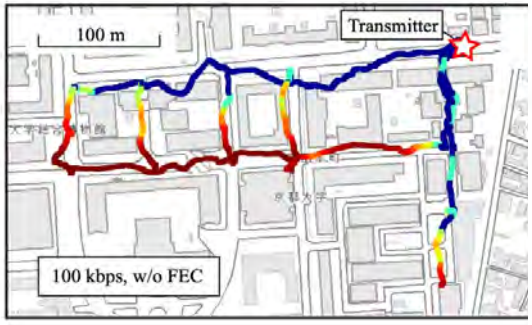
(a) Transmitter setup

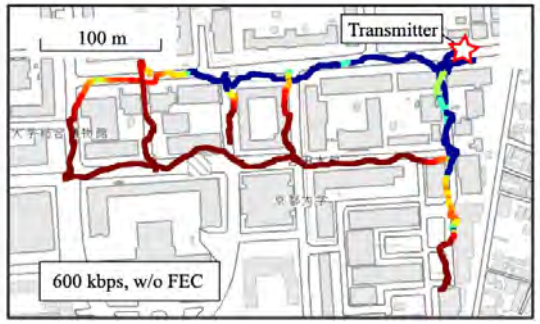
(b) Receiver setup

Antenna height: 4.5 m
Transmission power: 20mW
IEEE 802.15.4-SUN FSK

Antenna height: 1.1 m

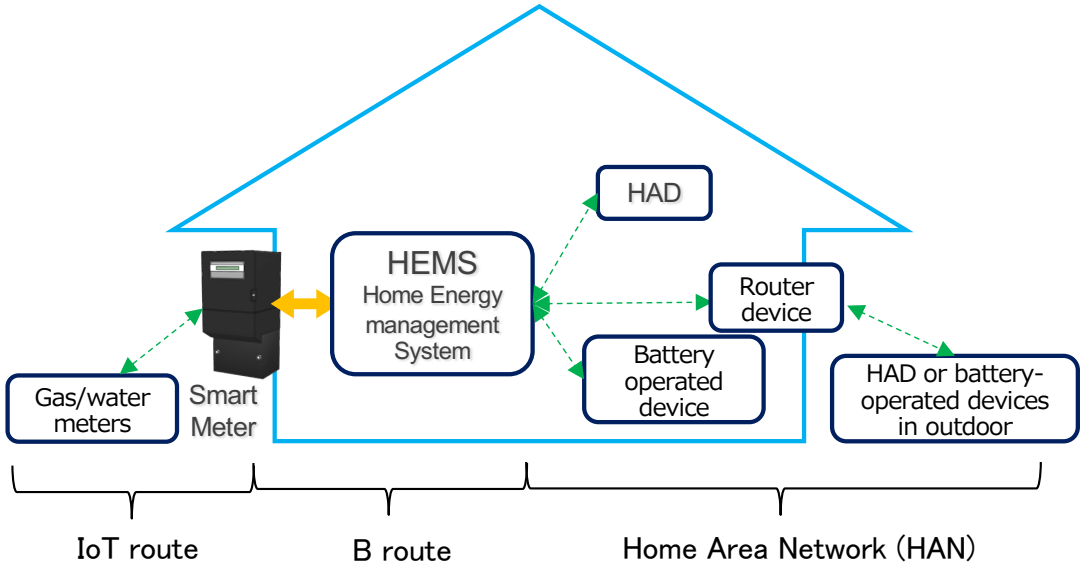






Y. Xiang, R. Okumura, K. Mizutani, and H. Harada, "Data Rate Enhancement of FSK Transmission Scheme for IEEE 802.15. 4-Based Field Area Network," IEEE Sensors Journal, Vol. 21, no.7, Jan. 2021

Main applications of Wi-SUN system
Home Area Network (HAN)



Application layer	ECHONET Lite
Access authentication	PANA (authentication＋Share encryption key)
Transport layer	UDP
Network layer	IPv6, ICMPv6
Adaptation layer	6LoWPAN
Datalink layer (MAC layer)	IEEE 802.15.10 Relay IEEE 802.15.4/4e
Physical layer	IEEE 802.15.4-2015 (920MHz, FSK, 100 kbps)

- **Standardized by Wi-SUN HAN and TTC JJ.300.10**
- B-route
  - Communication between smart meter and HEMS
  - Wi-SUN HAN (B-route) supported
- HAN(Home Area Network)
  - Communication between HEMS, home appliance devices, and battery-operated devices
  - One-hop relay is possible using a relay device.
- IoT route
  - Realize joint metering of electricity, gas, and water
  - Wi-SUN enhanced HAN supported

1st Generation smart meter installation plan in Japan

All JP power companies need to adopt Wi-SUN B-route when installing smart meters (over100 millions)

Region	Primary Technology	Secondary Technology
Hokkaido	920MHz Wireless (Wi-SUN IP system)	PLC (G3 PLC System)
Tohoku	920MHz Wireless (Wi-SUN IP system)	PLC (G3 PLC System)
Tokyo	920MHz Wireless (Wi-SUN IP system)	PLC (G3 PLC System)
Chubu	920MHz Wireless (Wi-SUN IP system)	PLC (G3 PLC System)
Hokuriku	920MHz Wireless (Wi-SUN IP system)	PLC (G3 PLC System)
Kansai	920MHz Wireless (Wi-SUN IP system)	PLC (G3 PLC System)
Chugoku	920MHz Wireless (Wi-SUN IP system)	PLC (G3 PLC System)
Shikoku	920MHz Wireless (Wi-SUN IP system)	PLC (G3 PLC System)
Kyushu	920MHz Wireless (Wi-SUN IP system)	PLC (G3 PLC System)
Okinawa	920MHz Wireless (Wi-SUN IP system)	PLC (G3 PLC System)

Utility providers have chosen the primary technology as the main approach, with secondary technology in consideration if the deployment is challenging for the former

Source: METI Smart Metering Report - http://www.meti.go.jp/committee/summary/0004668/pdf/015_03_00.pdf

1st Generation smart meter installation plan in Japan

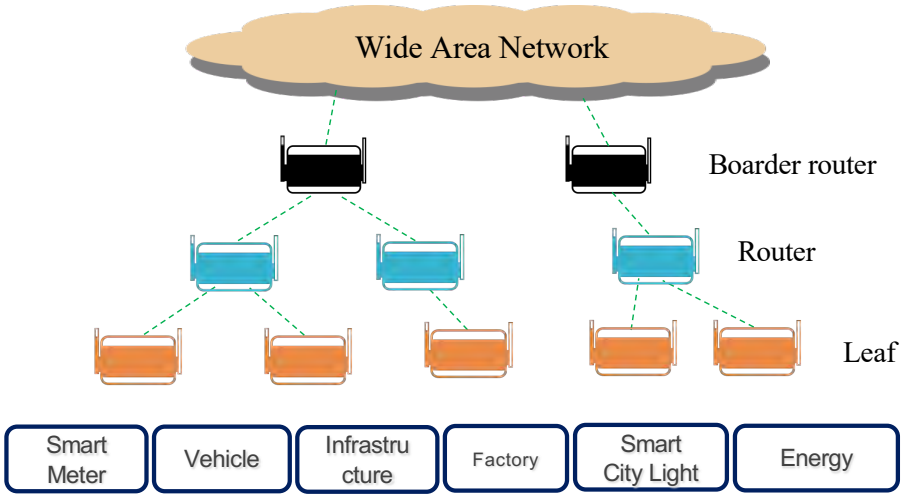
Region	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Hokkaido		380	530	480	490	510	510	520	560	570	
Tohoku	120	650	840	820	810	800	780	730	730	720	
Tokyo	1900	3200	5700	5700	5700	3300	3300				
Chubu	10	1020	1460	1440	1420	1390	1390	1420	1390		
Hokuriku		150	250	250	230	230	220	190	190	160	
Kansai	1600	1700	1700	1700	1500	1300	1300	1200	1100		
Chugoku		240	560	610	610	610	610	610	610	610	
Shikoku	30	150	310	310	310	310	310	310	310	300	
Kyushu			800	850	850	1090	1010	1000	890	790	
Okinawa		10	100	100	100	100	100	100	90	90	90

In units of 1000

Total number of smart meters to be deployed by end of 2020 expected to reach **66.86 million**

Source: METI Smart Metering Report - http://www.meti.go.jp/committee/summary/0004668/pdf/015_03_00.pdf

Main applications of Wi-SUN system Field Area Network (FAN)



- Border router (BR)
  - Wide Area Network (WAN) connectivity
  - Source routing table for all nodes within its Personal Area Network (PAN)
- Router
  - Upward and downward packet forwarding
  - Send and receive packets
- Leaf node
  - No child nodes connected
  - Only sending/Receiving packets

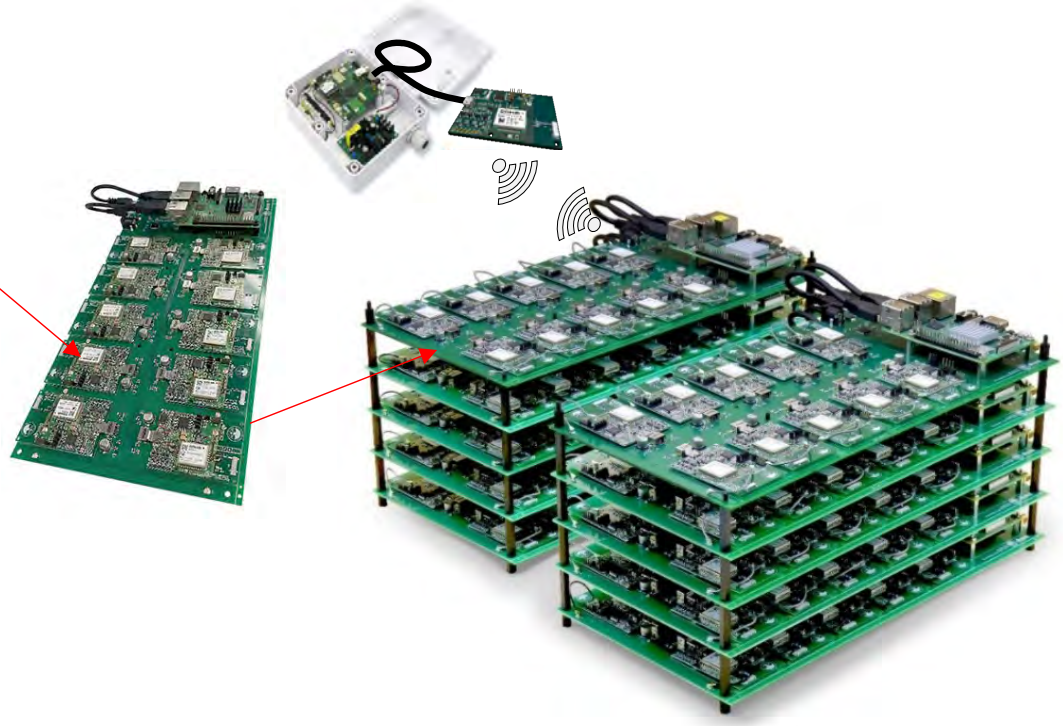
Application layer	**Up to venders or providers**
Access authentication	**IEEE 802.1X**
Transport layer	**UDP/TCP(option)**
Network layer	**Multihop: RPL IPv6, ICMPv6**
Adaptation layer	**6LoWPAN**
Datalink layer (MAC layer)	**IEEE 802.15.4/4e**
Physical layer	**IEEE 802.15.4-2015 FAN1.0: FSK FAN1.1: FSK and OFDM**

- **Standardized by IEEE 2857 and Wi-SUN FAN 1.0**
- Expansion of communication area through multi-hop with over 20 hops
- Even if devices are installed in close proximity to each other, interference between devices is avoided by frequency hopping.

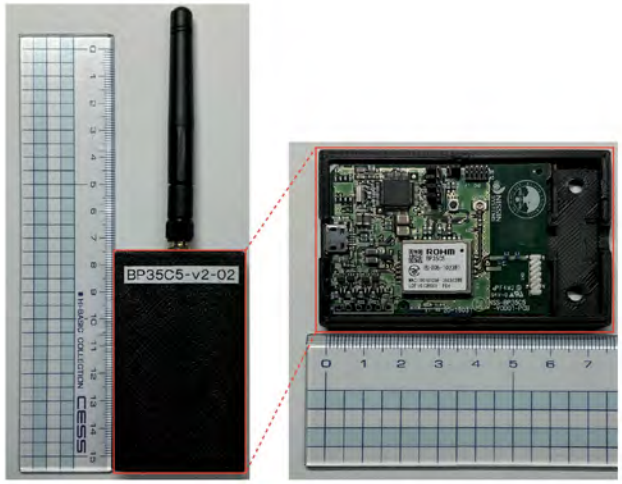
Development of Wi-SUN FAN

Wi-SUN FAN board (version 1.0 FSK-based)

Boarder router

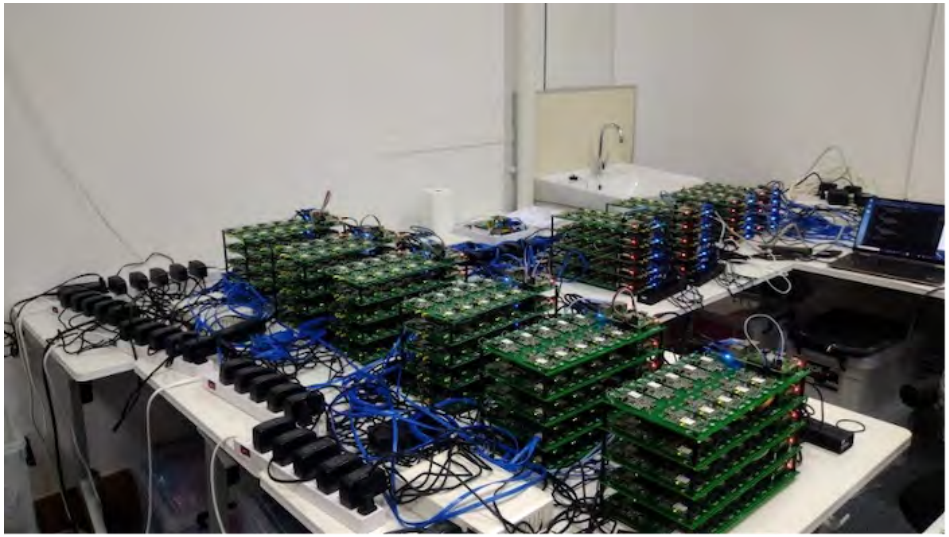


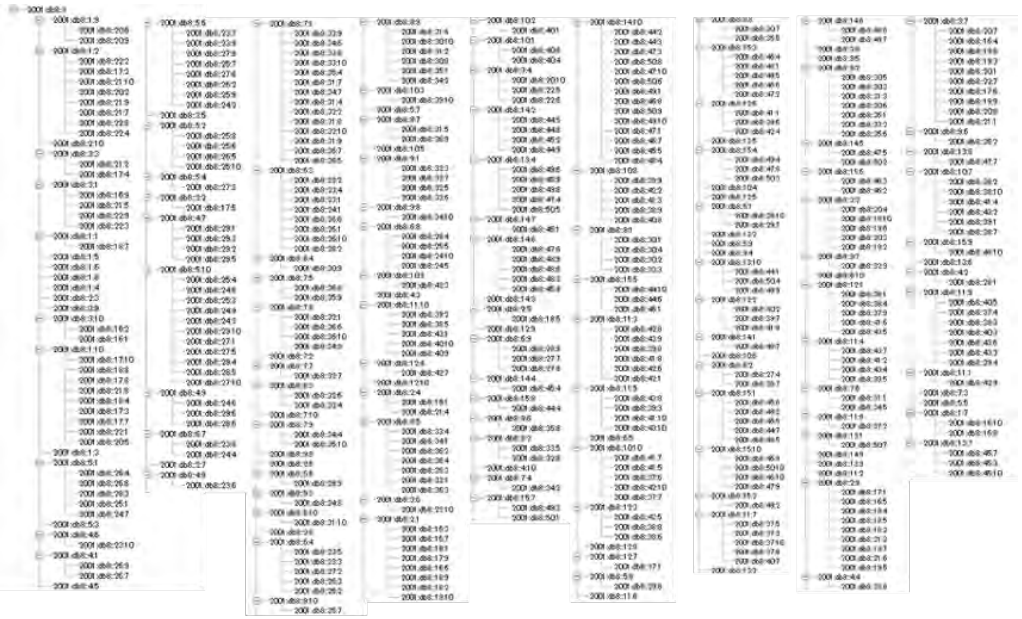
Wi-SUN FAN large scale evaluation system



Wi-SUN FAN radio unit

Wi-SUN FAN large scale evaluation with 500 units





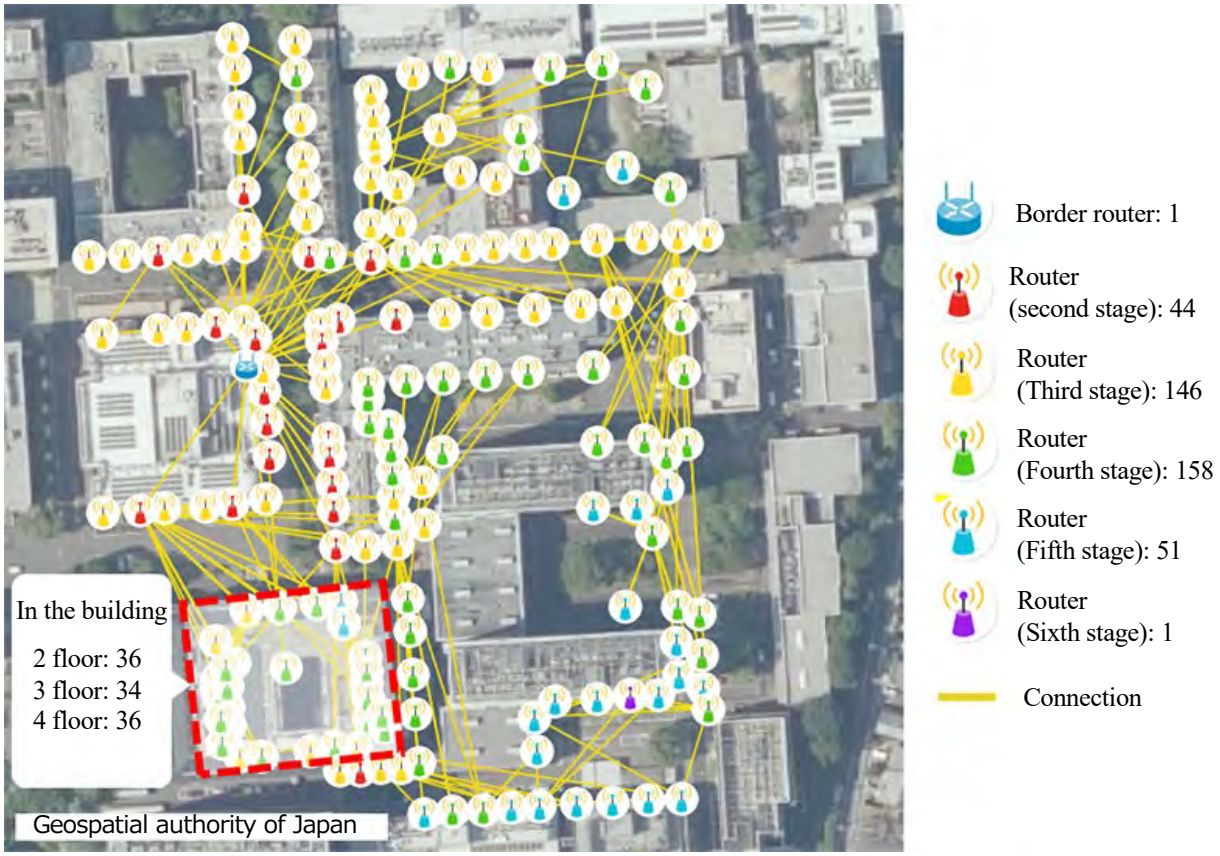
Press release by Kyoto Univ. and Nissin systems, Nov. 15, 2021

Demonstration

Wi-SUN FAN large-scale field trial with 400 units

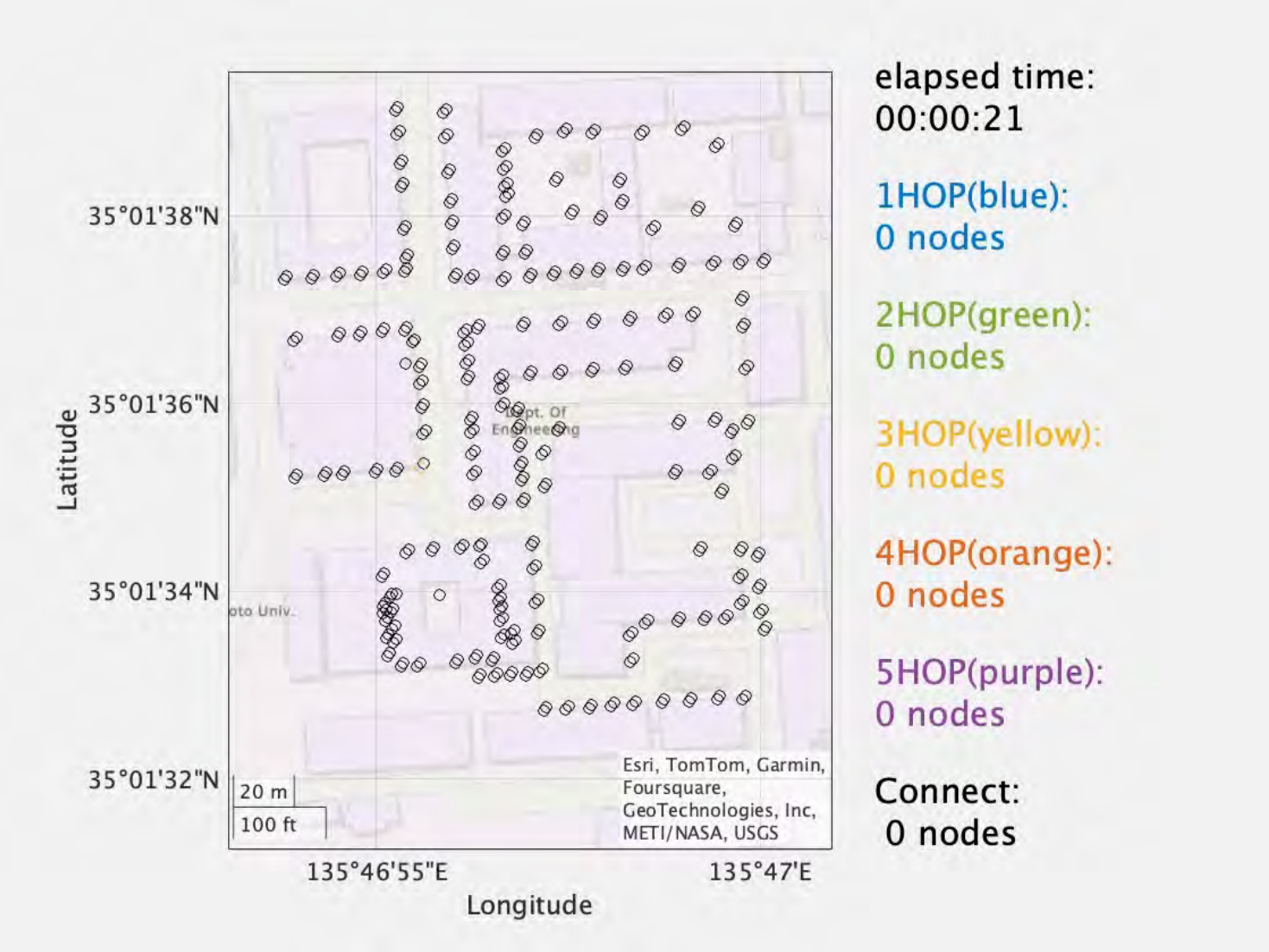
- 400 Wi-SUN FAN devices with mobile battery randomly placed in the field
- Continuous operation over several days
- Communication success rate of 97.1% or higher established

Wi-SUN radio device



Press release by Kyoto Univ. and Nissin systems, March 30, 2023

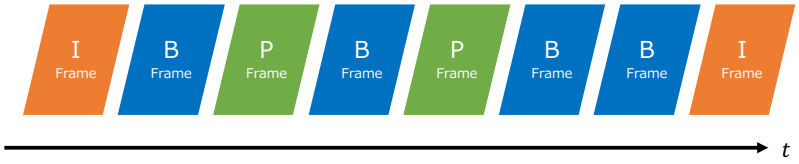
Demonstration with Wi-SUN FAN 400 nodes



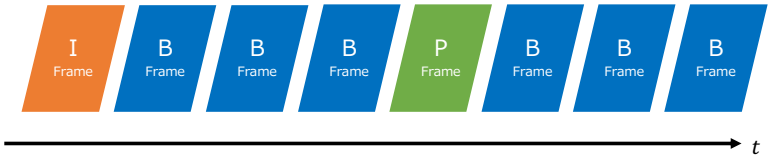
Wi-SUN FAN Next step: Video transmission

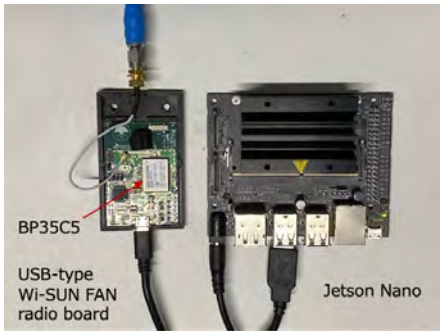
- A New Video transmission method is used [1]
  - According to the amount of image change between the frames, the I-frames are changed to P-frames and B-frames, and P-frames are changed to B-frames

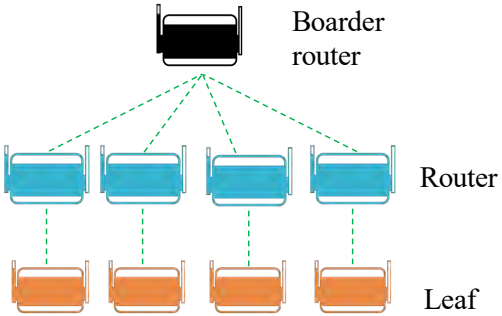
Conventional method



Proposed method







Leaf 1: 1280 × 720
Frame rate : 5 fps
Bit rate : 100 kbps

Leaf 2: 640 × 360
Frame rate : 5 fps
Bit rate : 50 kbps

Leaf 3: 640 × 360
Frame rate : 5 fps
Bit rate : 50 kbps

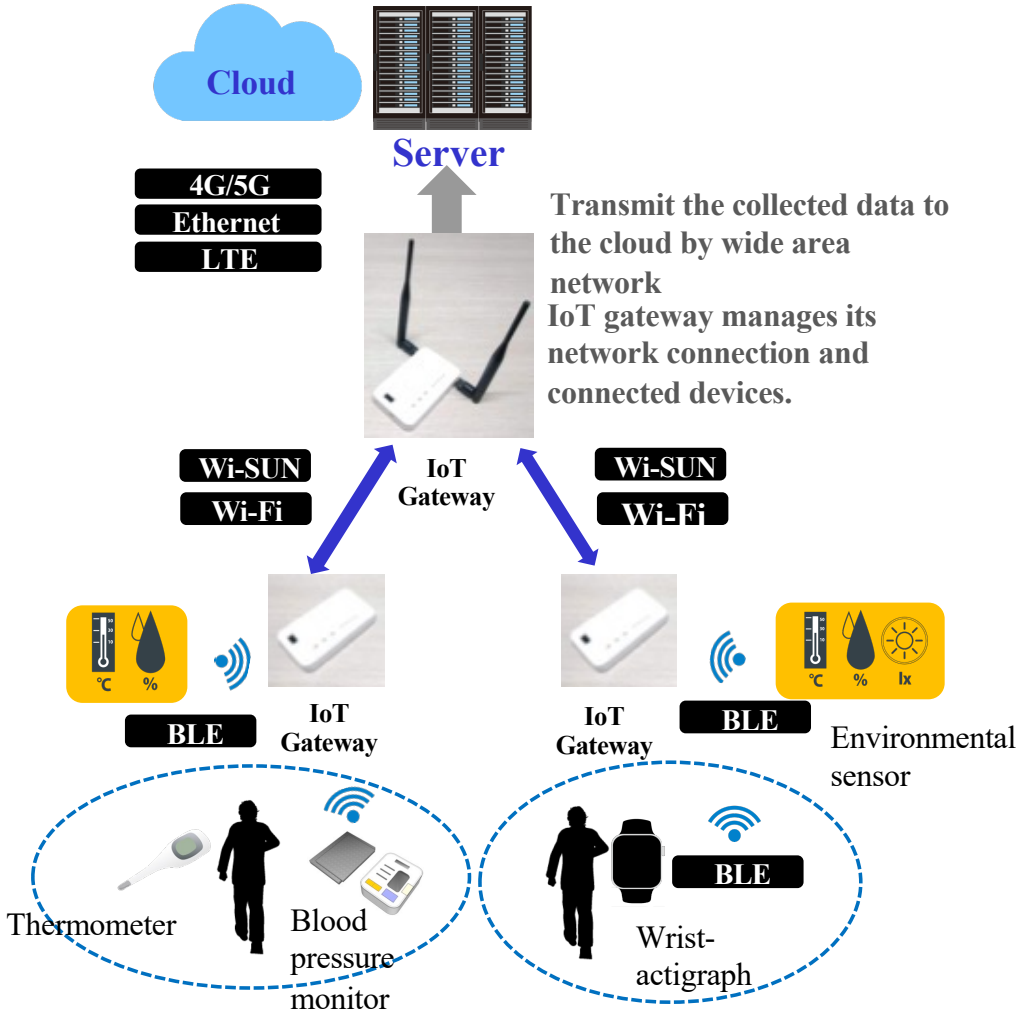
Leaf 4: 640 × 360
Frame rate : 5 fps
Bit rate : 50 kbps

Video source: NASA Image and Video Library. "The-Earth-4K-Extended-Edition MP4". https://images.nasa.gov/details-The-Earth-4K-Extended-Edition_MP4

[1] Reo Gakumi, Hiroko Masaki, Keiichi Mizutani, and Hiroshi Harada, "Video Transmission Trial by Wireless Multi-hop Network based on Wi-SUN FAN," Proc. WPMC 2022, Nov. 2022.

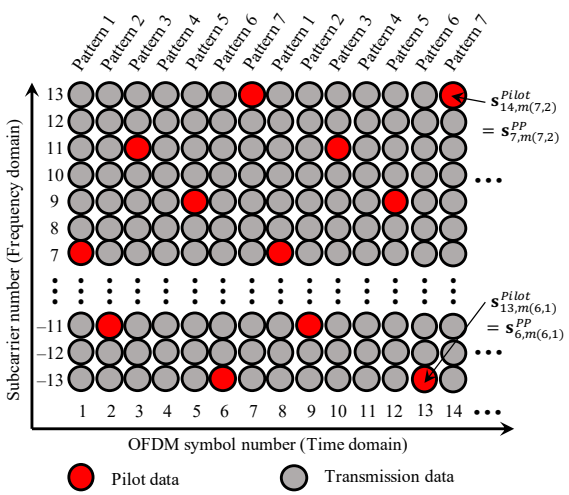
Wi-SUN FAN Next step: Wi-SUN router

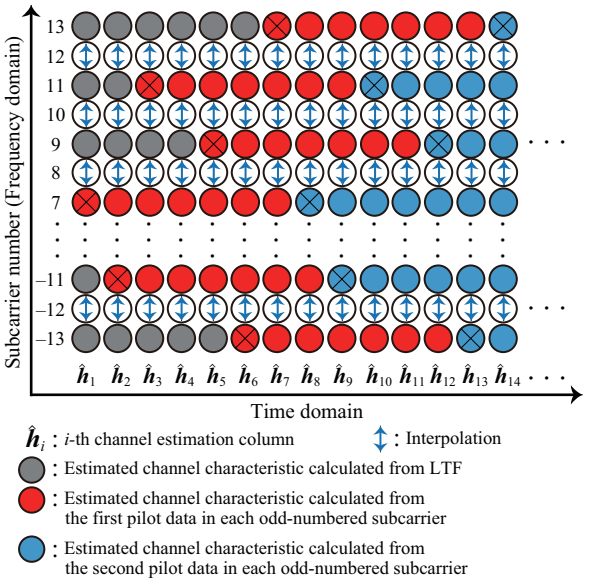
- Equipped with Wi-SUN FAN 1.0 certified by the Wi-SUN Alliance
  - Support 300 kbps FSK
  - Allows selection of internal or external antenna
  - Achieves high communication quality through Wi-SUN antenna diversity
- Equipped with Wi-Fi (Dual-Band 802.11 ac/a/b/g/n) and Bluetooth 5
- Supports power supply via USB Type-C and power supply via JST 2-pin connector (optional)



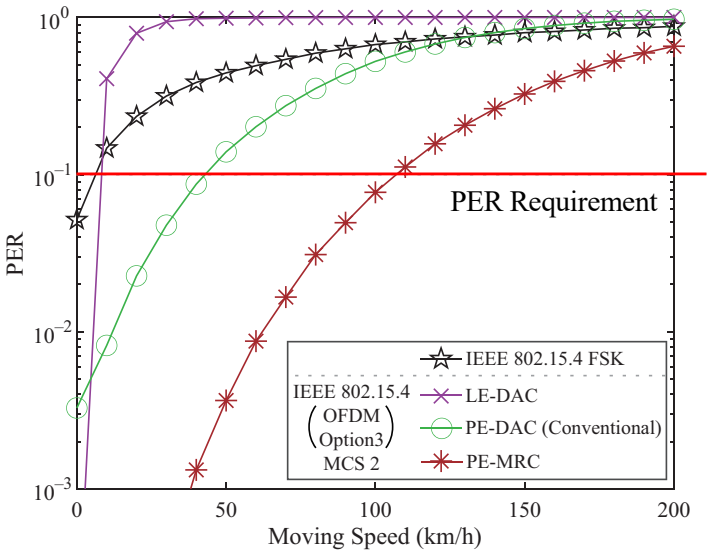
Wi-SUN FAN Next step: V2X communication

Improvement of channel estimation scheme





Wi-SUN at 100km/h is possible



	Parameter	Value
Common	PSDU length	250 octets
	Oversampling	16
	SNR (AWGN level)	37.8 dB
	Channel model	GSM Typical Urban
	Carrier frequency	920 MHz
	Moving speed	0–200 km/h
SUN-FSK	Modulation scheme	2-GFSK
	Preamble length	15 octets
	Data rate	100 kbps
	Modulation index	1.0
	Gaussian filter BT	Tx: 0.5, Rx: 0.5
	Encoding scheme	w/o FEC
SUN-OFDM	Option / MCS	3 / 2
	Decoding scheme	Viterbi (Soft decision)

Receive scheme	Channel estimation scheme	Diversity in Frequency domain
LE-DAC	LTF only	EGC
PE-DAC	Proposed scheme 1	EGC
PE-MRC	Proposed scheme 1	MRC
ePE-MRC	Proposed scheme 2	MRC

H. Ochiai, Y. Morikawa, K. Mizutani, H. Harada, “An Enhanced Channel Estimation for IEEE 802.15. 4 OFDM Receiver in High-speed Mobile IoT Communication Systems”, IEEE Internet of Things Journal, Feb. 2023.

Next Step … 802.15ad

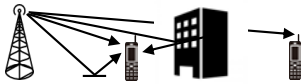
Large-scale Wi-SUN system emulation using a virtual space and digital twin with a wireless emulator

Wireless emulator

Difficult to evaluate the transmission performance of the wireless communication systems using the actual radio devices in the physical space of the B5G era.

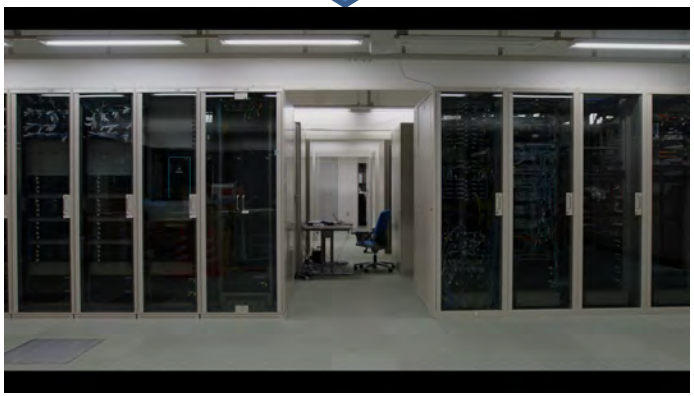
- When a large-scale wireless system with numerous wireless devices is examined in the future, **it becomes severely difficult to verify transmission characteristics using actual wireless devices.**
- When the verification of the large-scale system is performed **outdoors**, it becomes **difficult to secure a place** where many of these radio devices are installed; in addition, **the installation cost also increases**

Highly accurate emulation of radio wave propagation in virtual space



Emulation of wireless systems by software

Re-production the real environment in virtual space based on map and terrain data



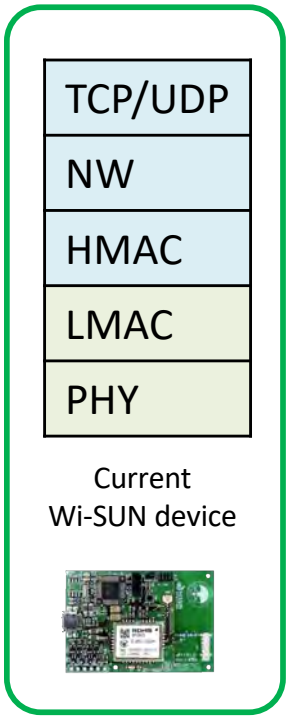
Wireless Emulator (NICT)

Real-time emulation in the virtual space built on the server

- Large-scale evaluation
- Verifying the actual radio equipment
- Emulation of multiple / heterogeneous systems
- Cost-cut of development, experiment, verification

Wireless Smart Utility Network (Wi-SUN)

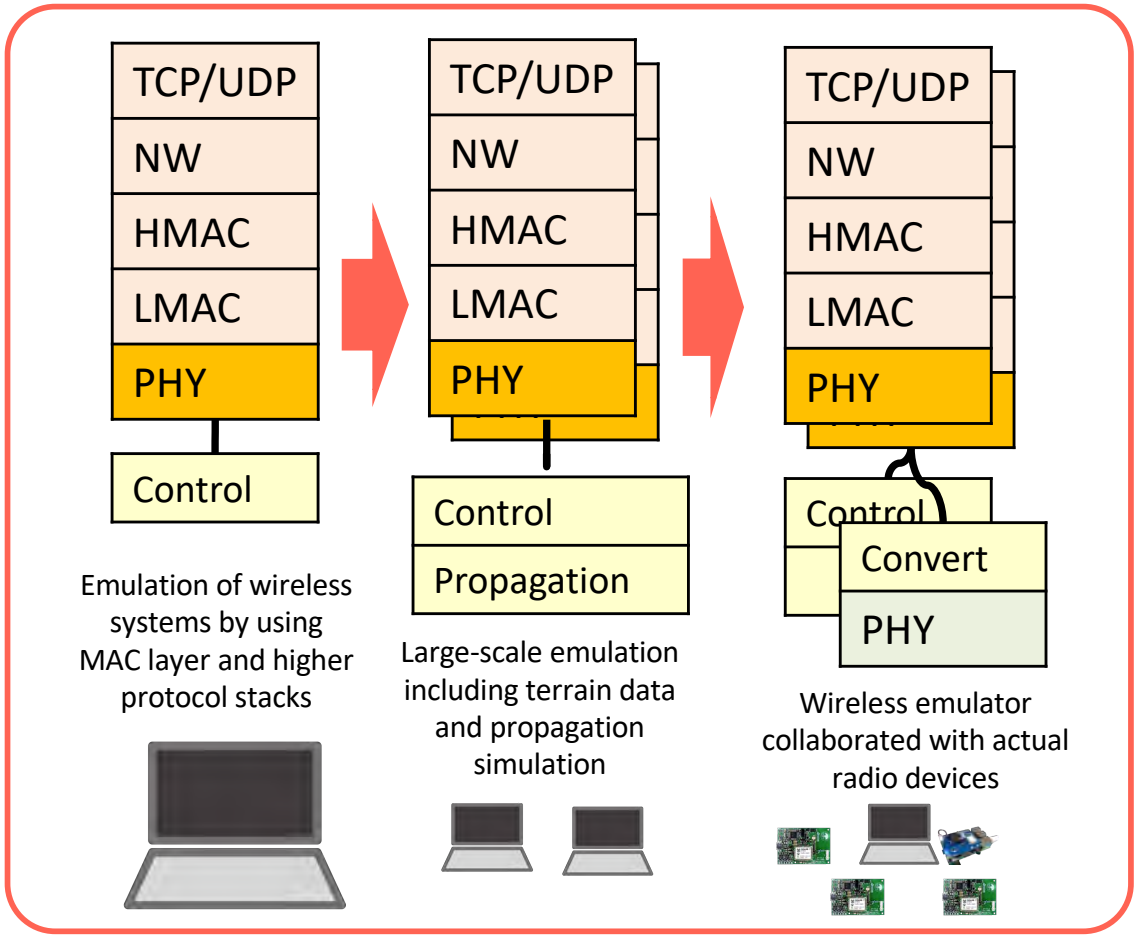
Wi-SUN device



Large-scale evaluation is performed by running the software installed on the actual device on wireless emulators as they are.

Install a large number of terminals in a virtual space, evaluate their transmission characteristics, and, install the modified parts on actual devices based on the results of the evaluation.

Wi-SUN virtual radio in wireless emulator



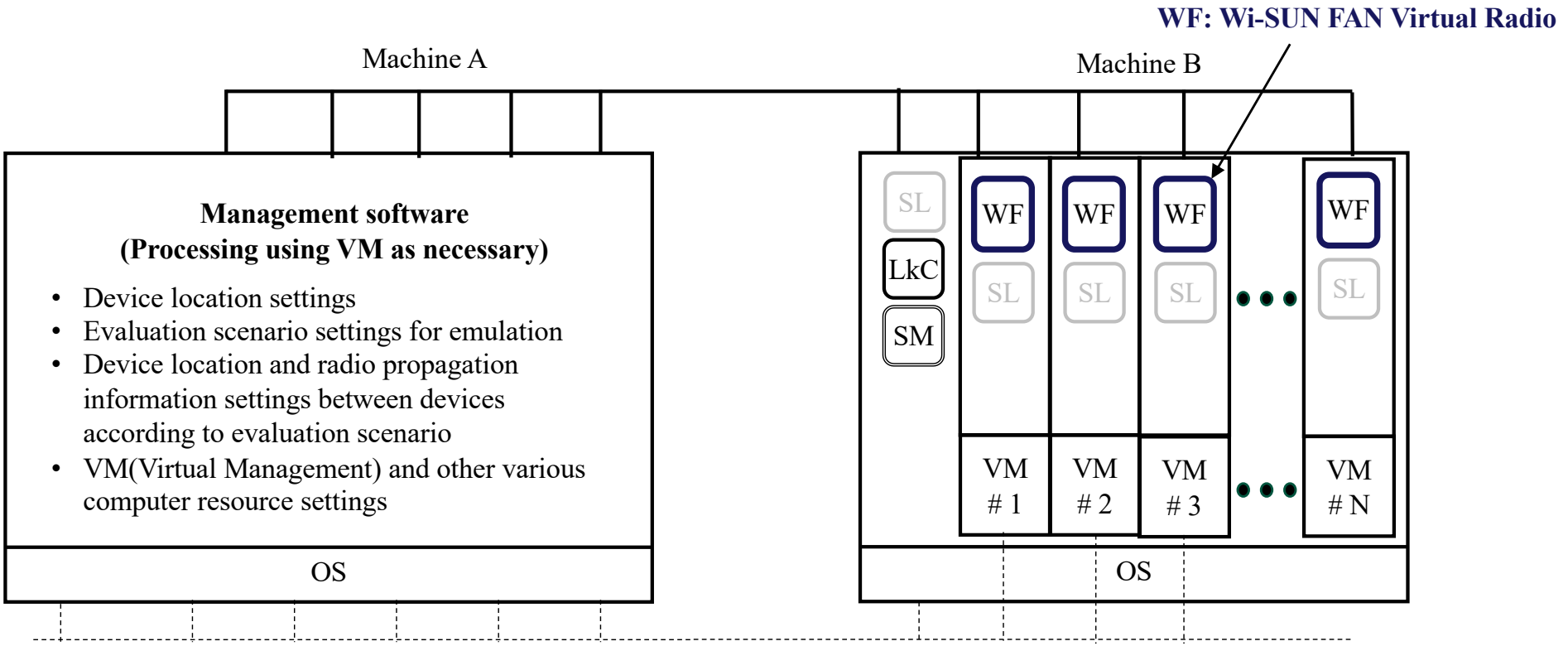
: Signal processing by hardware

: Signal processing by software on embedded OS

: Signal processing by software on OS used in wireless emulator (ex. Linux)

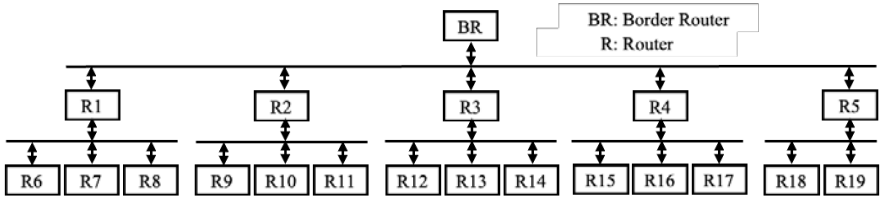
: Emulation by using virtualization on computers

Setup of Wi-SUN virtual radio to emulator

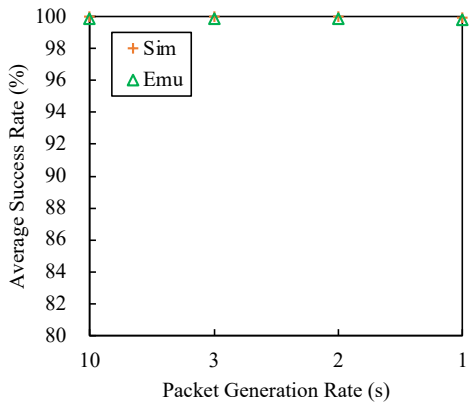


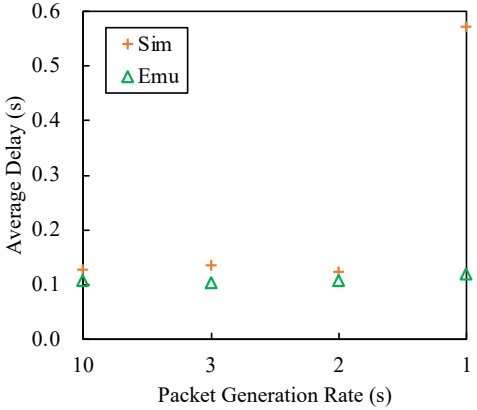
Calibration of wireless emulator

- Tree topology: 20 nodes (1 BR, 5 router, and 14 Leaf Routers)



Parameters	Values
Data rate (kbps)	150
Number of frequency hopping channels	14
DAO sending interval (s)	600
Number of data packets	100
Data packets size (byte)	200
Data packets generation rate (s)	1, 2, 3, 10

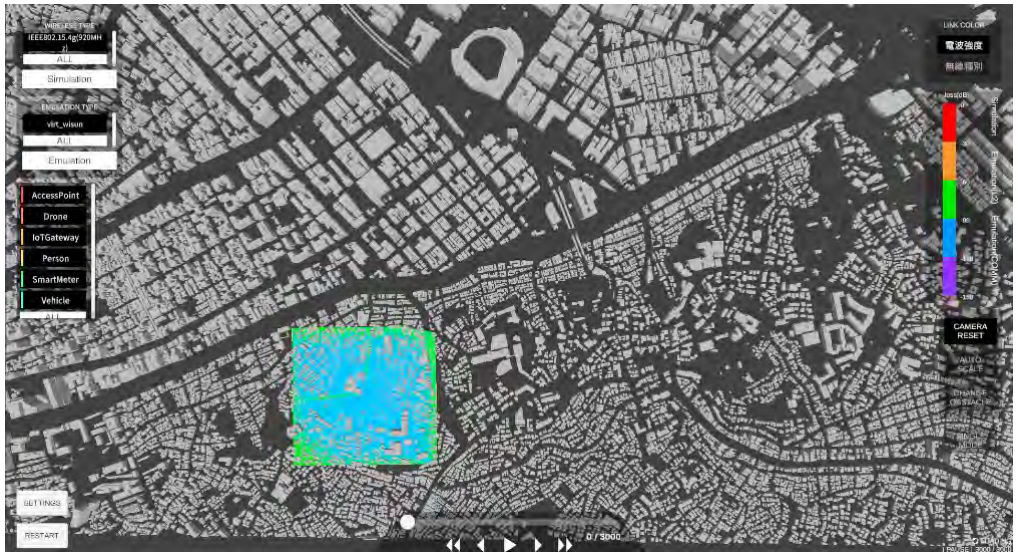




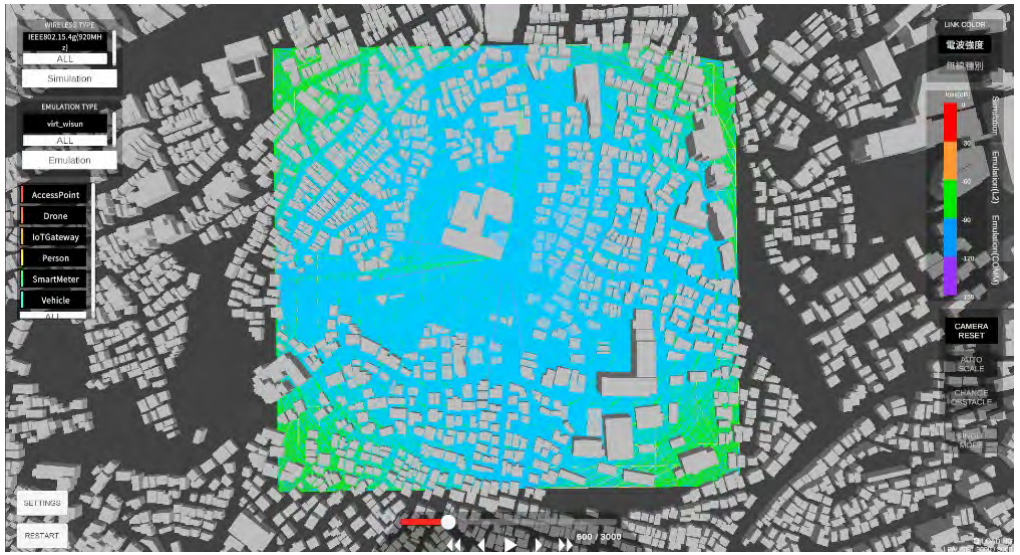
- This figure agrees with the computer simulation results programmed by [1] for validation.
- The average packet reception success rate and average transmission delay time essentially agree well with computer simulation results.
- Compared with star topologies, emulation delays are less than simulations because CSMA/CA determines the collisions in the emulation process

[1] R. Hirakawa, R. Okumura, K. Mizutani, and H. Harada, "A Novel routing Method with Load-Balancing in Wi-SUN FAN Network," in Proc. WF-IoT 2021, June. 2021.

Emulation of Wi-SUN systems by wireless emulator

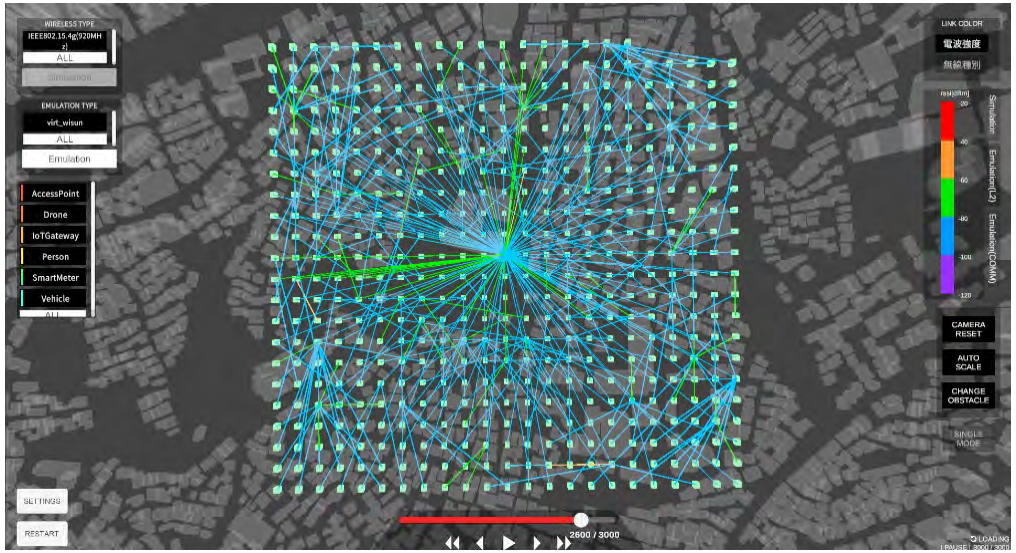


1. Installation of wireless virtual devices
(using 3D topographical data)
(500 Wi-SUN FAN systems installed in a residential area of Yokohama)

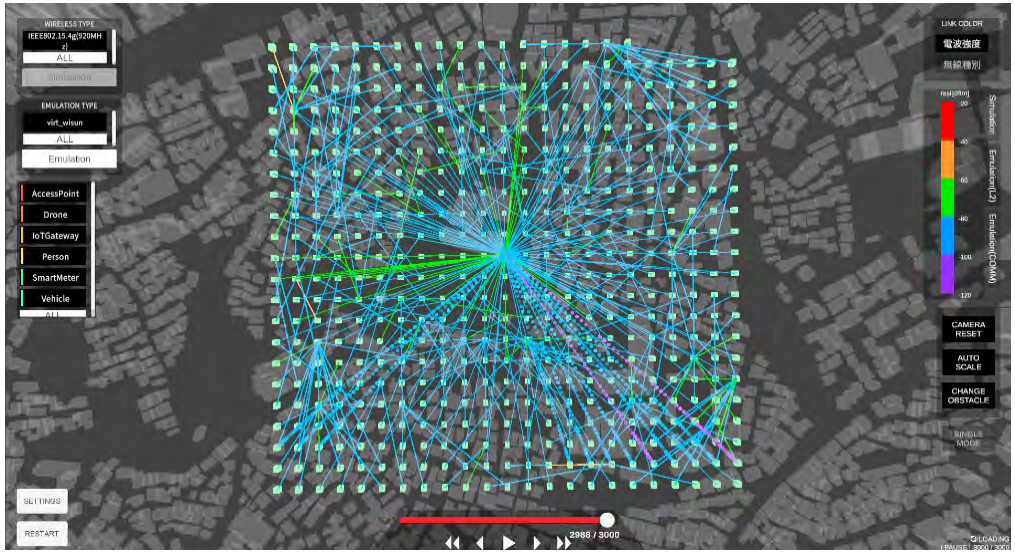


2. Calculate the transmission characteristics of all links
(using 3D topographical data)
(e.g. two waves of ground reflection + shadowing)

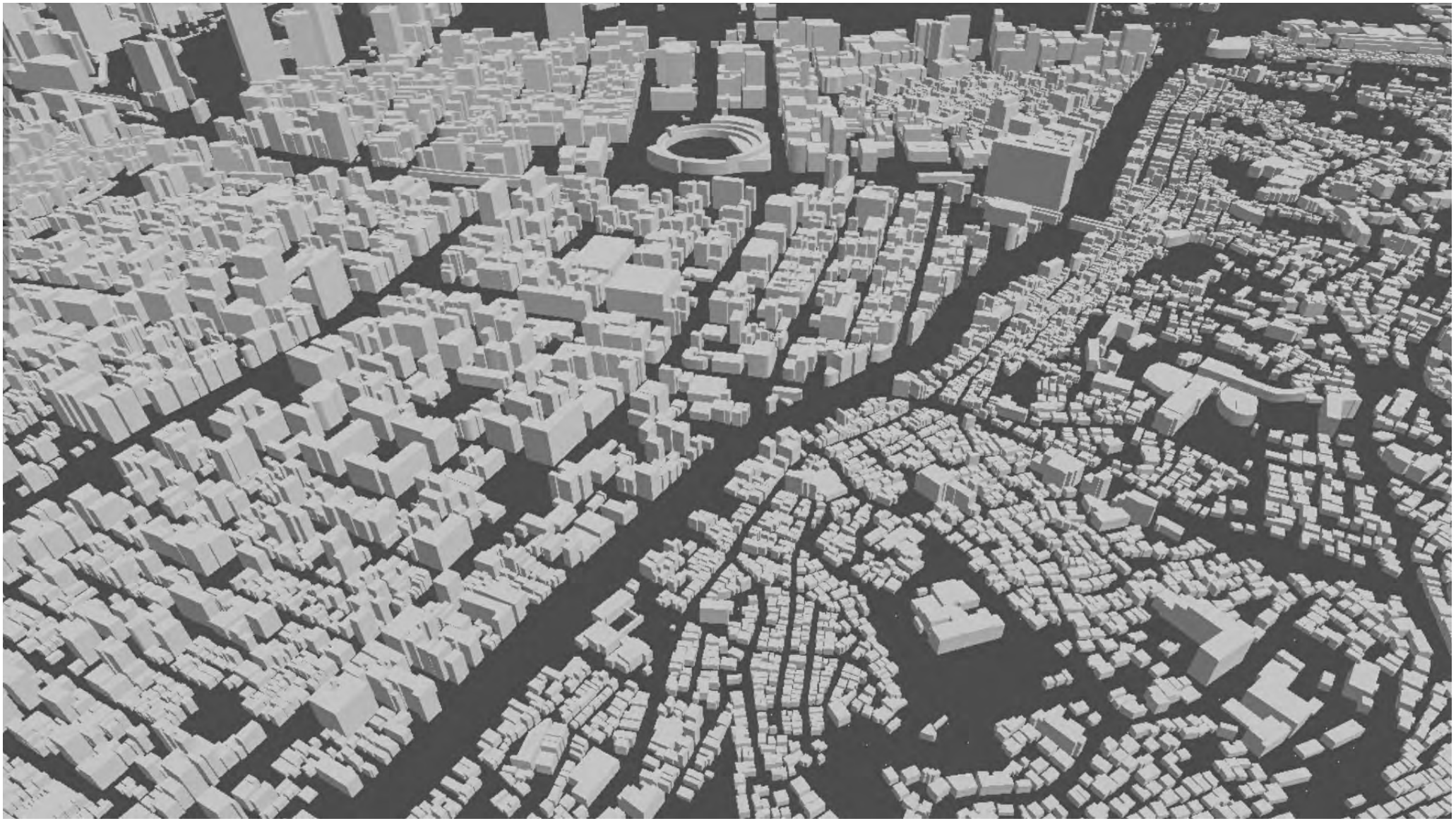
Emulation of Wi-SUN systems by wireless emulator



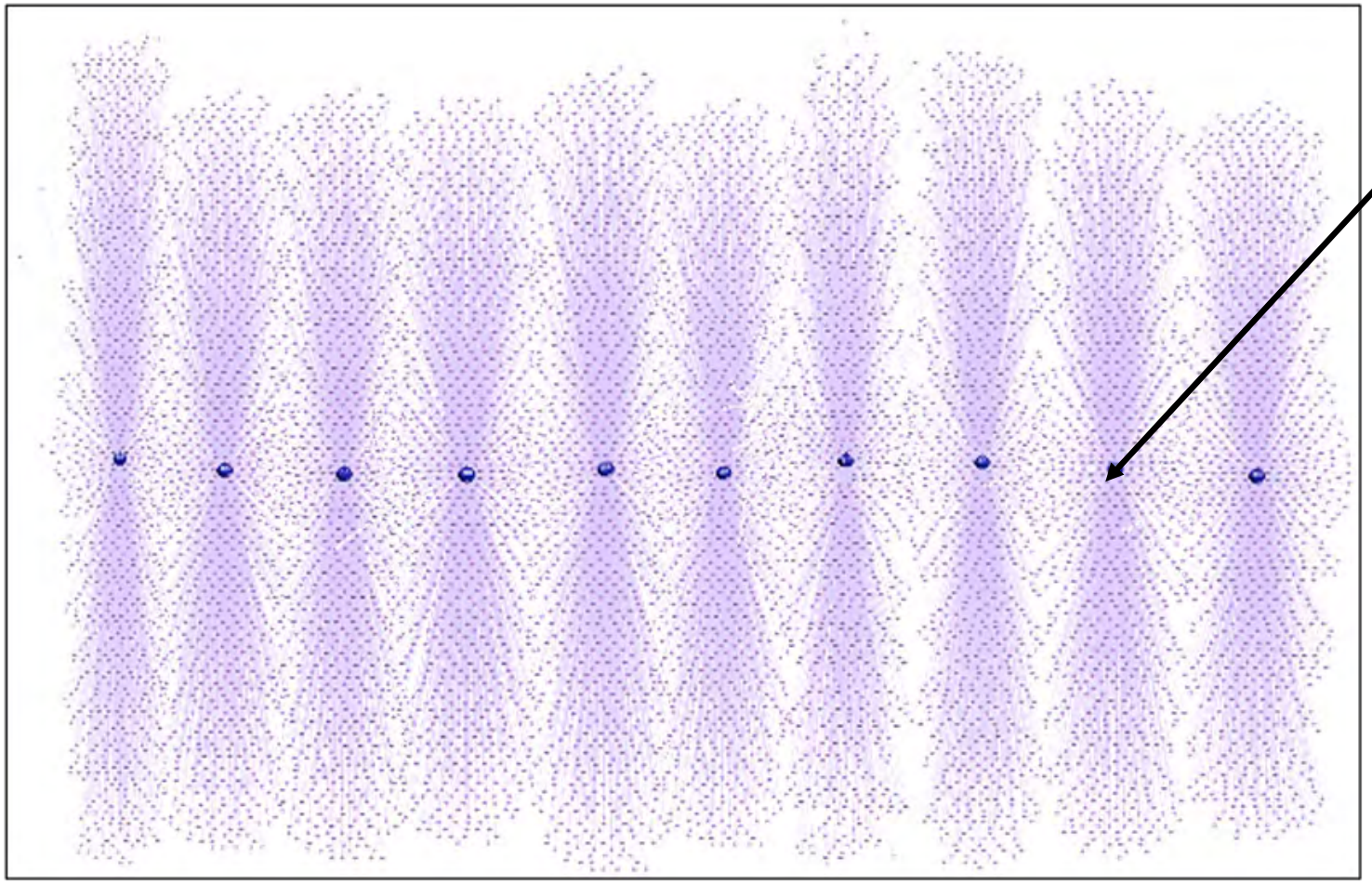
3. Building a mesh network using the Wi-SUN FAN protocol that can be installed on actual devices
(visualization of multi-hop formation status)



4. Packet transmission using the Wi-SUN FAN protocol that can be installed on actual devices
(visualization of transmission status)
[Solid line: route, dotted line: packet transmission]



Emulation using 10,000 Wi-SUN FAN virtual radio devices



Press release by Kyoto Univ., Jan. 31, 2024

Wireless emulator next step

Design of the location for installing wireless devices

Wireless emulator

1. Provide information on radio waves and installation environment
(transmission power, modulation/decoding method, antenna height, 3D map information, information on various fixtures in the map, information on the movement of people and objects)

2. Calculation of radio propagation and transmission characteristics between wireless devices in a 3D environment

3. Notification of calculation results

Users considering installing wireless devices

User
- Office
- Factory
- Intelligent Transport Systems (ITS)

4. Visualization of calculation results (through visualization tools in wireless emulators, visualization tools made by third parties)

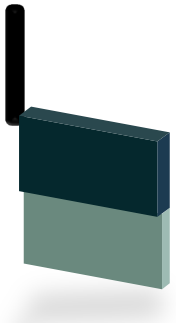
Equipment Certification for Radio Equipment

Wireless emulator

1. Provide information on the wireless communication standards and test items for which certification is desired, and connect the developer's wireless device (DUT)

2. Calculation of radio propagation and transmission characteristics between wireless devices in a 3D environment

3. Notification of calculation results



User
- Certification company
- Vender

4. Review the results of the evaluation through the log, and see whether the devices have passed the certification test or not.

Conclusions

- Wi-SUN HAN has been installed in tens of millions of devices in Japan, mainly in HAN
- HAN is currently only used for electricity meters, but it is planned to be used for joint meter readings of electricity, gas and water meters
- Wi-SUN FAN can build a mesh network with up to around 20 hops based on IEEE standards, which have been standardized by IEEE802.15 and IEEE 2857
- Wi-SUN FAN is expected to be used in Japan for Field Area Networks between outdoor electricity meters
- By installing Wi-SUN devices in wireless routers, new applications in fields such as medicine, agriculture and factories can be created.
- Wireless emulators are effective as a system that can be used to design large-scale Wi-SUN systems without outdoor experiments

As the Wi-SUN system is a large-scale commercialized system developed by the IEEE 802.15.4 community, it will require continuous expansion in 802.15 community in the future