Advanced Wireless & Communication Research Center

ACTIVITY REPORT 2022

The University of Electro-Communications

Message from the Director, Prof. Takeo Fujii

The Convid-19 disaster is slightly improved in 2022; faculties and students of Advanced Wireless Communication Research Center (AWCC) return to the office and the ratio of face-to-face meeting dramatically inreases. In our research communities, face-to-face international conferences and domestic workshops are returned. The activities of international conference presented by members of AWCC were dramatically increased comared with statistics during the period of corona. The activity publishing journal papers also keep high level in 2022. We also tackle several national projects including beyond 5G, low power sensor networks and cooperative autonomous vehicles in 2022.

For the years, AWCC has been aiming and conducting four missions that are;

- Dedication to advanced research on wireless communications; offering more unique results.
- Education in graduate school for cultivating specialty in engineering; specialized and universal education in the area.
- Active collaboration / joint research with industries and government; transferring the outcomes to the society.
- Constant acquisition of competitive research funds; for self-supported operation.

The current vision of AWCC is “Ambient Wireless in Connected Community (AWCC).” AWCC intends to cover broader research area including not only wireless communications but also any promising aspects of “wireless” and “communications”. As an academic institute, it is our mission to pursue basic research in science and technology. Toward the goals, AWCC will enhance its force and strengthen its presence in the world.

We are focusing the following four research sectors.

(1) Wireless Technology as Social Infrastructure

Wireless technologies will have more importance in the society as the base of safe, secure and smart life for the individual and the community. Intelligent Transport System (ITS) is one of the focused topics, anticipating the great demand for automated driving.

(2) Innovative Hardware for Wireless & Communication

Demands for broadband and high-capacity mobile communication systems are very strong, and 5G and beyond system is being developed in the world. The 5G and beyond system introduces new usage of frequency spectra called multi-band multi-access, which requires innovation in RF hardware to achieve higher-accuracy signal transmission with flexibility. Also, wireless power transfer is another hot and important topic.

(3) Advanced Wireless System & Networks

We have developed many fundamental technologies such as distributed dynamic multi-hop network, cognitive radio, fault-tolerant network operation, and radio environment-aware communications. From now on, we integrate the technologies and establish an ultimate wireless network design.

(4) Exploring Low Power Wireless

By reducing power consumption of wireless system dramatically, applications of wireless communications will spread wider than now. It will make all things connected in the world, realizing the word "IoT". Innovative low-power technologies are necessary to realize such a world.

As the open research center to the society, AWCC would like to think together with people and contribute much in research and education of “wireless” and “communications”. We hope your kind help and great understanding to AWCC.

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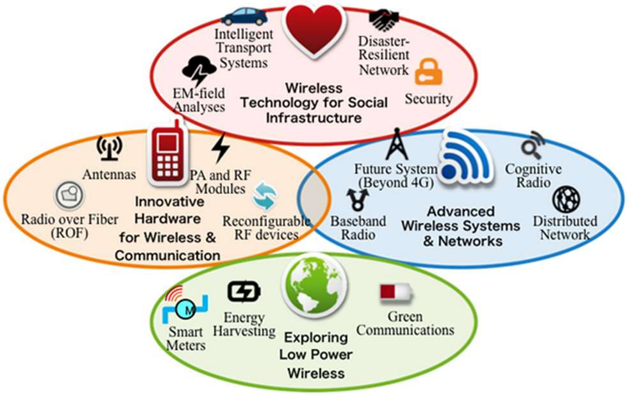
1 . ABOUT AWCC

1.1 OVERVIEW

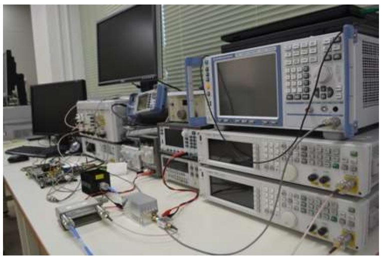


The Advanced Wireless Communication Research Center (AWCC) was launched in April 2005 with the aims of establishing a global hub for wireless communications; advancing education in wireless technology; industrial collaboration and technology transfer; and nurturing young engineers with strong emphasis on both theoretical and experimental aspects of wireless communications. In April 2015, the center was re-launched as the Advanced Wireless and Communication Research Center with the same abbreviation, AWCC, to enhance its remarkable range of activities over the previous ten years. With funding of approximately 1000 million yen over nine years, the center consists of 4 full time, 5 concurrent, 20 cooperative, and 6 visiting professors. In addition, there are 9 visiting professors from industry and more than 100 graduate students, post-doctoral and research fellows. The center actively contributes to academic societies and publishes more than 150 papers annually in top journals and proceedings of international conferences.

The AWCC organizes regular seminars and workshops with the highlight of 2014 being the "Tokyo Wireless Technology Summit" held in March 2014. The meeting focused on the next major phase of mobile telecommunications called 5th generation (5G) and attracted approximately 240 participants from all over the world.

1.2 FACILITIES

AWCC is located on the east-campus of the University of Electro-Communications in Chofu city, Tokyo near Shinjuku district in Japan. The center has opened with 10,441 square foot of modern research space containing a class room, two conference rooms, four research offices, and two experiment rooms with a wide range of instruments including FPGA development platforms, signal generators, vector network analyzers, spectrum analyzers, software defined radios, and so on. Also, it has extensive computer and network resources including high-speed workstations and personal computers which are integrated with resources of the Univeristy of Electro-Communications.



1.3 PEOPLE

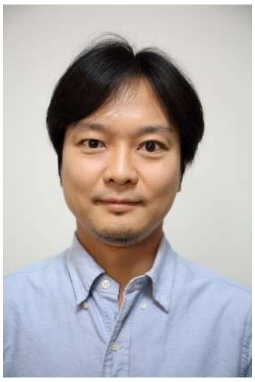
【Director, Full-time Prof. Takeo Fujii】

Takeo Fujii was born in Tokyo, Japan, in 1974. He received the B.E., M.E. and Ph.D. degrees in electrical engineering from Keio University, Yokohama, Japan, in 1997, 1999 and 2002 respectively. From 2000 to 2002, he was a research associate in the Department of Information and Computer Science, Keio University. From 2002 to 2006, he was an assistant professor in the Department of Electrical and Electronic Engineering, Tokyo University of Agriculture and Technology. From 2006 to 2014, he has been an associate professor in Advanced Wireless Communication Research Center, The University of Electro-Communications. Currently, he is a professor in Advanced Wireless and Communication Research Center, The University of Electro-Communications. His current research interests are in cognitive radio and ad-hoc wireless networks. He received Best Paper Award in IEEE VTC 1999-Fall, 2001 Active Research Award in Radio Communication Systems from IEICE technical committee of RCS, 2001 Ericsson Young Scientist Award, Young Researcher's Award from the IEICE in 2004, The Young Researcher Study Encouragement Award from IEICE technical committee of AN in 2009, Best Paper Award in IEEE CCNC 2013, and IEICE Communication Society Best Paper Award in 2016. He is a member of IEEE and a fellow of IEICE.

【Full-time Prof. Koji Ishibashi】

Koji Ishibashi received the B.E. and M.E. degrees in engineering from The University of Electro-Communications, Tokyo, Japan, in 2002 and 2004, respectively, and the Ph.D. degree in engineering from Yokohama National University, Yokohama, Japan, in 2007. From 2007 to 2012, he was an Assistant Professor at the Department of Electrical and Electronic Engineering, Shizuoka University, Hamamatsu, Japan. Since April 2012, he has been with the Advanced Wireless Communication Research Center (AWCC), The University of Electro-Communications, Tokyo, Japan where he is currently an Associate Professor. From 2010 to 2012, he was a Visiting Scholar at the School of Engineering and Applied Sciences, Harvard University, Cambridge, MA. Prof. Ishibashi has contributed more than 100 articles to international journals and conference proceedings. His current research interests are grant-free access, non-orthogonal multiple access (NOMA), millimeter wave communications, ultra-low power communications, signal processing, and information theory. He is a senior member of IEEE and IEICE.

【Full-time Associate Prof. Koichi Adachi】



Koichi Adachi received the B.E., M.E., and Ph.D. degrees in engineering from Keio University, Japan, in 2005, 2007, and 2009 respectively. His research interests include cooperative communications and energy efficient communication technologies. From 2007 to 2010, he was a Japan Society for the Promotion of Science (JSPS) research fellow. He was the visiting researcher at City University of Hong Kong in April 2009 and the visiting research fellow at University of Kent from June to Aug 2009. From May 2010 to May 2016, he was with the Institute for Infocomm Research, A*STAR, in Singapore. Currently, he is an associate professor at The University of Electro-Communications, Japan. He was an Associate Editor IEEE Wireless Commun. Lett. between 2016 – 2022, IEEE Trans. Veh. Technol. between 2016 – 2018, IEEE Trans. on Green Commun. and Net. between 2016 – 2022, IEEE Open J. of Veh. Technol. since 2019. He is a senior member of IEEE and a member IEICE. He was recognized as the Exemplary Reviewer from IEEE Wireless Commun. Lett. in 2012, 2013, 2014, and 2015. He is a coauthor of WPMC2020 Best Student Paper Award.

【Full-time Associate Prof. Kun Li】(Joined on 1st Apr. 2023)

Kun Li received the B.E. degree in communication engineering from the Nanjing University of Posts and Telecommunications, Nanjing, China, in 2011, and the M.E. and Ph.D. degrees in electrical engineering from the University of Toyama, Toyama, Japan, in 2014 and 2017, respectively.

From 2017 to 2019, he was a Researcher with the Electromagnetic Compatibility Laboratory, National Institute of Information and Communications Technology, Tokyo, Japan. From 2020 to 2023, he was an Assistant Professor with the Faculty of Engineering and Design, Kagawa University, Takamatsu, Japan. He was a Visiting Researcher with the CNRS/IETR, University of Rennes 1, Rennes, France, from 2022 to 2023. In 2023, he joined the Advanced Wireless and Communication Research Center, The University of Electro-Communications, Tokyo, Japan, where he is currently working as an Associate Professor. His research interests include electromagnetic computation and measurement for radiation safety by human exposure to electromagnetic fields in radio frequencies, antenna design and measurement techniques for wireless body area network system. Dr. Li was the recipient of the Young Scientist Award of the URSI, in 2020, the Risaburo Sato Award of EMC Sapporo & AMPEC, in 2019, the IEEE AP-S Japan Student Award in 2015, and the IEICE Best Letter Award in 2017. He is a member of IEEE International Committee on Electromagnetic Safety TC95 and Co-Chair of Working Group 7 under Subcommittee 6 EMF Dosimetry Modeling established to study average schemes and assessment methods of absorbed power density. He is a senior member of URSI and a member of IEEE and IEICE.

【Concurrent Prof. Koichiro Ishibashi】

Koichiro Ishibashi has been a professor of The University of Electro-Communications, Tokyo, Japan since 2011. He received PH. D degree from Tokyo Institute of Technology in 1985. He joined Central Research Laboratory, Hitachi Ltd. in 1985, where he had investigated low power technologies for Super H microprocessors and high density SRAMs. From 2004 to 2011, he was in Renesas Electronics where he developed low power IPs mainly for mobile phone SOCs as a department manager.

He has presented more than 110 academic papers at international conferences including ISSCC, IEDM invited papers, and IEEE Journals. He was awarded R&D 100 for the development of SH4 Series Microprocessor in 1999. He is a member of IEICE and a Fellow of IEEE.

His current interests include design technology of low power LSI, and IoT applications using the low power LSIs. They include low power design technology using SOI devices and energy harvesting sensor networks.

【Concurrent Prof. Koji Wada】

Koji Wada received the B.E. and M.E. degrees from Kinki University, Osaka, Japan, in 1991 and 1995, respectively, and the Doctorate degree from Yamaguchi University, Yamaguchi, Japan, in 1999. From 1999 to 2004, he was a Research Associate with the Department of Electrical Engineering and Electronics, Aoyama Gakuin University, Kanagawa, Japan. From 2004 to 2015, he worked as an Associate Professor at the Department of Electronic Engineering, the University of Electro-Communications, Tokyo, Japan and he is Currently a Professor at the Department of Computer and Network engineering, Graduate School of Informatics and Engineering, the University of Electro-Communications. His research interests include resonators, filters, multiplexers, multiband circuits, tunable circuits, periodic structure, and metamaterial circuits. Dr. Wada is a member of the Institute of Electronics, Information and Communication Engineers (IEICE), Japan, Institute of Electrical Engineers of Japan (IEEJ), and Japan Institute of Electronics Packaging (JIEP).

【Concurrent Prof. Motoharu Matsuura】

Motoharu Matsuura received the Ph.D. degree in electrical engineering from the University of Electro-Communications, Tokyo, Japan, in 2004. In 2007, he joined the Department of Information and Communication Engineering at the University of Electro-Communications as an Assistant Professor. From 2010 to 2011, on leave from the university, he joined the COBRA Research Institute, Eindhoven University of Technology, Eindhoven, The Netherlands, as a Visiting Researcher, where he studied ultrahigh-speed optical signal processing using semiconductor-based devices. He is currently a Professor with the Graduate School of Informatics and Engineering, Department of Communication Engineering and Informatics, University of Electro-Communications. His research interests include optical signal processing, photonic subsystems, and radio-over-fiber transmission systems. He is the author or coauthor of more than 180 papers published in international refereed journals and conferences. He received the Ericsson Young Scientist Award in 2008, the FUNAI Information Technology Award for Young Researcher in 2009, and the Telecommunication System Technology Award of the Telecommunications Advancement Foundation in 2011. He is a member of IEEE, OSA, and IEICE.

【Concurrent Prof. Ryo Ishikawa】

Ryo Ishikawa received the B.E., M.E., and D.E. degrees in electronic engineering from Tohoku University, Sendai, Japan, in 1996, 1998, and 2001, respectively. In 2001, he joined the Research Institute of Electrical Communication, Tohoku University, Sendai, Japan. In 2003, he joined the University of Electro-Communications, Tokyo, Japan. His research interest is the development of microwave compound semiconductor devices and related techniques. He was the recipient of the 1999 Young Scientist Award for the Presentation of an Excellent Paper of the Tohoku Chapter, Japan Society of Applied Physics.

【Concurrent Prof. Celimuge Wu】

Celimuge Wu received his PhD degree from The University of Electro-Communications, Japan, where he is currently a professor. His research interests include Vehicular Networks, Edge Computing, IoT, Intelligent Transport Systems, and AI for Wireless Networking and Computing. He serves as an associate editor of IEEE Transactions on Network Science and Engineering, IEEE Transactions on Green Communications and Networking, and IEEE Open Journal of the Computer Society. He is the Vice Chair (Asia Pacific) of IEEE ComSoC Technical Committee on Big Data (TCBD), and the chair of IEEE TCGCC Special Interest Group on Green Internet of Vehicles. He is a recipient of 2021 IEEE Communications Society Outstanding Paper Award, 2021 IEEE Internet of Things Journal Best Paper Award, IEEE Computer Society 2020 Best Paper Award and IEEE Computer Society 2019 Best Paper Award Runner-Up. He is a senior member of IEEE.

【Concurrent Associate Prof. Katsuya Suto】

Katsuya Suto received the B.Sc. degree in computer engineering from Iwate University, Morioka, Japan, in 2011, and the M.Sc. and Ph.D. degrees in information science from Tohoku University, Sendai, Japan, in 2013 and 2016, respectively. He has worked as a Postdoctoral Fellow for Research Abroad, Japan Society for the Promotion of Science, in the Broadband Communications Research Lab., University of Waterloo, ON, Canada, from 2016 to 2018. He is an Associate Professor with the Graduate School of Informatics and Engineering, the University of Electro-Communications, Tokyo, Japan. His research interests include semantic communications, radio propagation, deep learning, and graph representation. He received the Best Paper Award at the IEEE VTC2013-spring, the IEEE/CIC ICCC2015, the IEEE ICC2016, and the IEEE Transactions on Computers in 2018. He is currently the Associate Editor of the International Journal of Computers and Applications. He is a member of IEEE and IEICE.

【Visiting Professors】

Prof. Yasushi Yamao, Ph.D.

Prof. Kazuhiko Honjo, Ph.D.

Prof. Yoichiro Takayama, Ph.D.

Prof. Akira Saito, Ph.D.

Prof. Masashi Hayakawa, Ph.D.

Prof. Hiroshi Suzuki, Ph.D.

Prof. Mitsuo Makimoto, Ph.D.

Prof. Giuseppe T. F. de Abreu, Ph.D.

Prof. Nobuo Nakajima, Ph.D.

Prof. Yukitsuna Furuya

Prof. Takayuki Inaba, Ph.D.

Prof. Tadashi Matsumoto, Ph.D.

【Cooperative Professors】

Prof. Haruhisa Ichikawa, Ph.D.

Prof. Naoto Kishi, Ph.D.
Prof. Tetsuro Kirimoto, Ph.D.
Prof. Kazuo Sakiyama, Ph.D.
Prof. Fengchao Xiao, Ph.D.
Prof. Xi Zhang, Ph.D.
Prof. Cong-Kha Pham, Ph.D.
Associate Prof. Manabu Akita, Ph.D.
Associate Prof. Yoshiaki Ando, Ph.D.
Associate Prof. Toshiharu Kojima, Ph.D.
Associate Prof. Hisa-Aki Tanaka, Ph.D.
Associate Prof. Kazuki Nishi, Ph.D.
Associate Prof. Satoshi Ono, Ph.D.
Associate Prof. Suhua Tang, Ph.D.
Associate Prof. Hayato Yamaki, Ph.D.
Associate Prof. Zhi Liu

【Visiting Professors from Industry】
Prof. Kunio Uchiyama (AIST)
Prof. Takahiro Asai (NTT Docomo)
Prof. Yoji Kishi (KDDI Research Inc.)
Prof. Terunao Soneoka (NTT-AT)
Prof. Akinori Taira (Mitsubishi Research Institute Inc.)
Prof. Hiroyuki Tsuji (NICT)
Prof. Hideki Hayashi (Softbank Corp.)
Prof. Hiroyuki Seki (Fujitsu Laboratory Ltd.)
Prof. Kenji Yoshida (Intermedia Laboratory Inc.)

2.1 Division of Wireless Technologies as Social Infrastructure

2.1.1 Purpose of Research

Wireless technologies will have more importance in the society as the base of safe, secure and smart life for individuals and community. Various types of machine to machine communication such as sensors, IoT devices and vehicular communications will spread in the society taking little notice but support safety and secureness of society, as well as creating more comfortable and smarter life. In these days, done communications are also focused on new infrastructures such as flying car, logistics and flying base stations and communications supporting drone is one of the important issues. In this division, technologies for realizing reliable and high capacity communication for supporting social infrastructure are developed.

2.1.2 Research Staffs and Their Specialties

Prof. Takeo Fujii (Division Leader, ITS, Radio Environment Recognition, Wireless Security)
Prof. Koji Ishibashi (Wireless Security)
Associate Prof. Koichi Adachi (Drone)
Associate Prof. Katsuya Suto (ITS)

2.1.3 Major Research Outcomes in 2022

[Observation Data and 3D Map-based Radio Environmental Recognition] (Fujii Lab.)
In Beyond 5G / 6G, which is being researched and developed as the next-generation mobile communication system, non-terrestrial networks (NTNs) are attracting attention. At NTNs, drones are expected to be used for a variety of purposes. For efficient drone wireless communication, it requires the estimation of the radio environment in the 3-dimensional space where drones fly. Although radio propagation models based on empirical rules have been traditionally used for radio environment estimation, has a problem that they do not consider information on surrounding structures and terrain. Recently, 3D maps have been used as location information. 3D maps have structure and terrain information. In this study, we propose a method for estimating the received power in the direction of altitude by combining 3D map information with observations obtained from actual drone flights. the proposed method estimates received power from observed value and diffraction loss which is calculated by using the 3D map and location information. Fig. 2.1-1 shows the system model of this study.

From the result of the measurement campaign for the LTE base stations, we conducted in Feb. 2023, the proposed method reduces the RMSE (Root Mean Squared Error) between estimated values and observed values up to 3.23[dB] from the conventional method which uses the empirical model. Table 2.1-1 shows the RMSE average of the proposed method and conventional method for each PCI (Physical Cell ID) when observed data are obtained randomly.

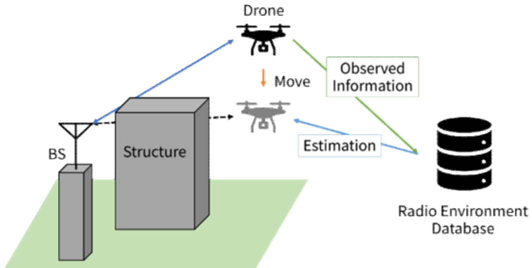


Fig. 2.1-1 System model.

Table 2.1-1 Average RMSE of each method.

PCI 113	
Conventional (Ext. Hata)	Proposed
9.60	6.37
PCI 145	
Conventional (Ext. Hata)	Proposed
7.23	4.68

[Realtime Channel Congestion Estimation from Communication Log] (Fujii Lab.)

Even if the received signal power is large, sometimes the throughput of LTE and 5G is degraded due to channel congestion of other users. In particular, we can understand this situation at the train station during rush hour and the data rate of a smart phone degrades. The throughput degradation is usually caused by the channel congestion at the base station connected by large number of users. A radio environment map generated by statistical value of each location can predict the average received power of the wireless signal from the base station but the channel congestion cannot be statistically obtained because of various user distribution. Therefore, real time channel congestion estimation is required.

In this research we estimate the channel congestion from the communication log at the terminal like smart phone, mobile router in the recent period. Here, we focus on the RSRQ (Reference Signal Received Quality) value, which is obtained by the ratio of RSRP (Reference Signal Received Power) to RSSI (Received Signal Strength Indicator). Usually, RSRP can remove the effect interference power but RSSI includes the influence of interference. So that the RSRQ degrades if the channel congestion occurs. Thee possibility of the estimation of congestion from RSRQ is measured at near the rail road of commuter train as shown in Fig. 2.1-2. We show the experimental results in Fig.2.1-3, in which, the relation between throughput and RSRQ of LTE system is shown. We can understand that the higher RSRQ has good throughput performance and the lower RSRQ has low throughput performance. From these results, we can confirm the possibility of the channel congestion estimation from RSRQ on LTE system.

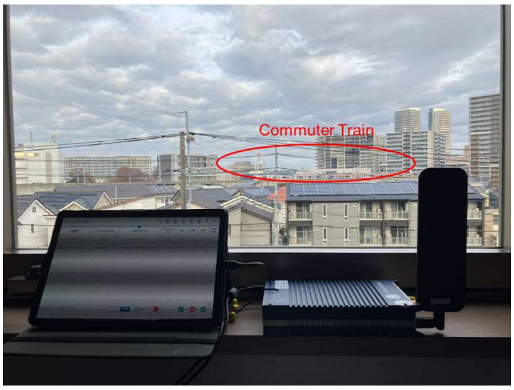


Fig.2.1-2 Measurement environment.

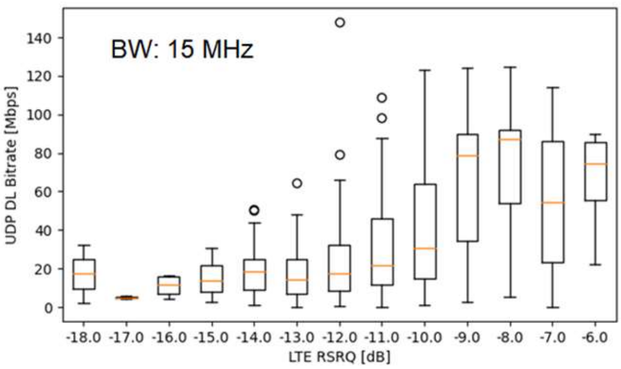


Fig.2.1-3 Relation between throughput and RSRQ on LTE system.

【Cyber-Physical Integrated Emulator for Cooperative Automated Driving】(Suto Lab.)

Cooperative automated driving using vehicle-to-everything (V2X) communications is a promising solution for future transportation systems because it can improve the safety of driving by cooperative perception, i.e., collection of surrounding information that cannot be obtained by self-equipped sensors. However, the performance and accuracy of cooperative perception are affected by the quality of service (QoS) of V2X communications. Toward the promising transportation system, we developed a network emulator that accurately evaluates QoS using physical information collected from the real world. Specifically, our developed emulator has the following features:

1. Multi-modal traffic simulator is integrated into the network simulator to analyze the interdependency between vehicle mobility and V2X QoS.
2. Actual measurement data in the real world is incorporated to emulate site-specific wireless environments.
3. Any applications using V2X communications can be developed in the platform to emulator cooperative automated driving services, i.e., behavior arbitration, speed advisory, etc.

Fig. 2.1-4 shows the overview of the developed emulator in which we employ simulation of urban mobility (SUMO) and NS3 as traffic and network simulators, respectively. The emulator can evaluate site-specific wireless environments using actual measured signals. For instance, we can evaluate a spatial-fading effect and consider the handover situation of mobile terminals, thereby improving the accuracy of QoS evaluation.

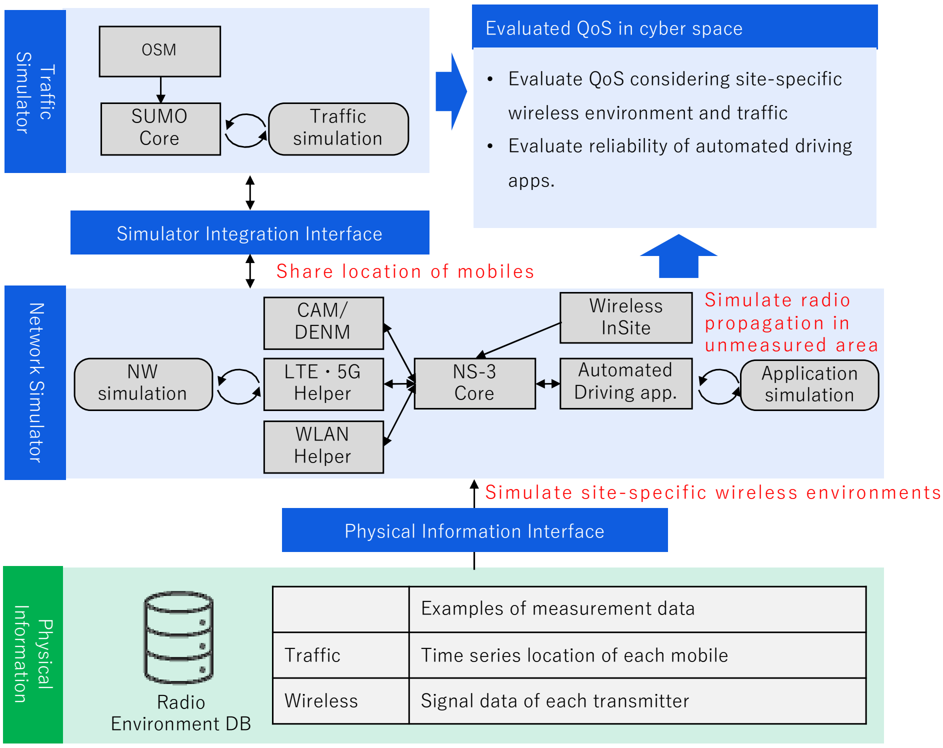


Fig. 2.1-4 Overview of cyber-physical integrated emulator.

【3D Radio Map Construction for Drone Networks】(Suto Lab.)

Recently, mobile communication systems have been used for drone services, e.g., video transmission, remote control, etc. However, non-terrestrial radio propagation, i.e., communication between a base station and drone, has yet to be well studied. To address the challenge, we developed a drone-based sensing system and measured non-terrestrial radio propagation at our university. Fig. 2.1-5 shows the measured radio map. We can see that the signal strength drastically changed due to the building, i.e., shadowing. Future more, we can find that the spatial correlation of the x-axis direction is higher than that of the z-axis direction. Fig. 2.1-6 demonstrates the interpolation accuracy of ordinary Kriging. We can see that ordinary Kriging can achieve enough estimation accuracy even with the use of 5% measured grids (4 measured grids) and gain the estimation accuracy with the increase of measured grids.

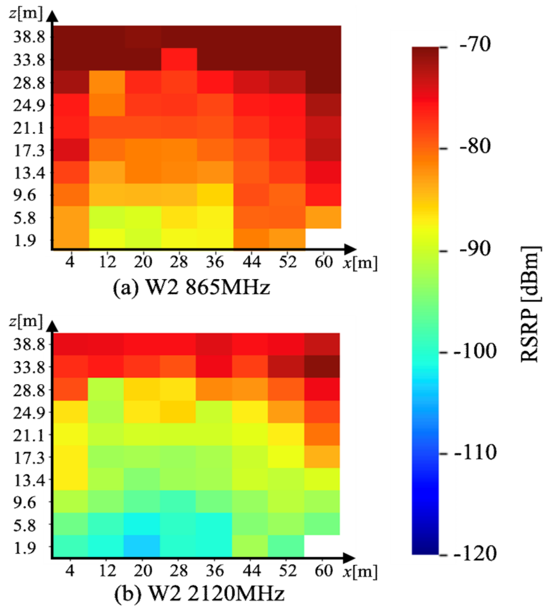


Fig. 2.1-5 Measured radio map.

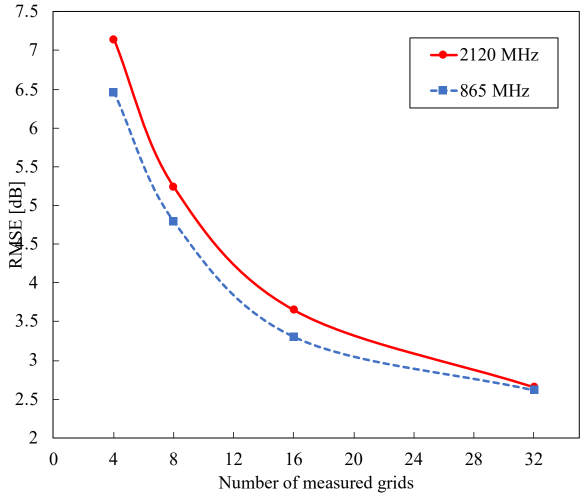


Fig. 2.1-6 Interpolation accuracy.

[Secure Precoded OFDM Transmission for Next-Gen. IoT Systems] (Koji Ishibashi Lab.)

To protect private information in next-generation IoT systems, physical layer security (PLS) is a promising option. This academic year, we considered a single-input, single-output wiretap channel model comprising a legitimate transmitter (Tx), a legitimate receiver (Rx), and an eavesdropper (Eve) in downlink transmissions with orthogonal frequency division multiplexing (OFDM) and proposed the secure symbol-wise precoding using a random unitary matrix with the *virtual* carrier frequency offset (CFO). Rx can easily equalize the received signals using priori knowledge of the CFO and achieve a lower error rate performance than conventional approach by enjoying the frequency diversity. Meanwhile, Eve has to estimate the virtual CFO besides to the transmitted data from one OFDM symbol, and this makes the Eve's estimation problem underdetermined. Fig.2.1-7 and Fig.2.1-8 quantitatively confirm that our proposed PLS scheme is more secure than conventional approaches in terms of bit error rate (BER) and achieves the positive secrecy capacity (SC) even assuming the Eve's precise knowledge about the virtual CFO.

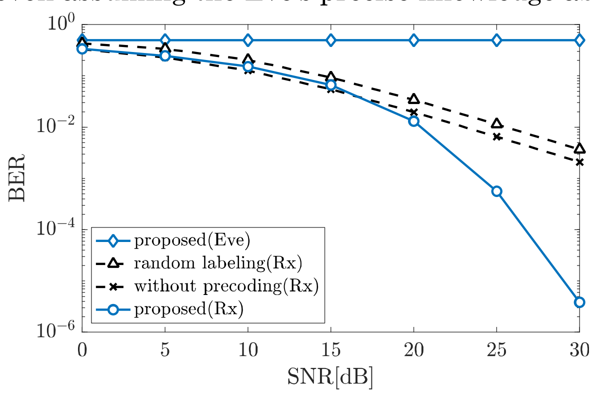


Fig2.1-7 SNR vs. BER comparisons.

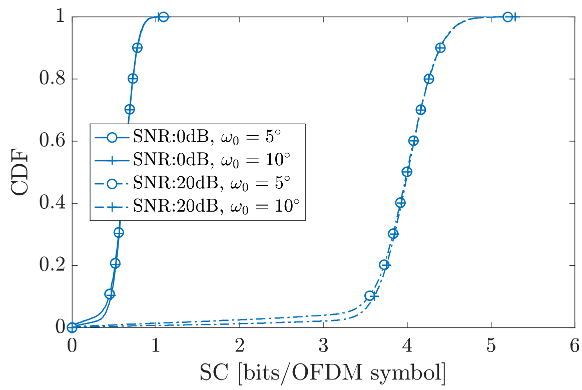


Fig 2.1-8 Achievable CDFs of SC considering maximum estimation error at Eve (ω_0).

2.1.4 Funds

【Grants-in-Aid for Scientific Research】

1. Scientific Research C “Research on Energy Efficient Wireless Communications Network Using UAV-BS”
   Koichi Adachi

【Commissioned Research】

1. METI Project on Research, Development, Demonstration and Deployment (RDD&D) of Autonomous Driving toward the Level 4 and its Enhanced Mobility Services (RoAD to the L4), “Harmonization and interoperability of V2V and V2P for deployment of L4 in mixed traffic environment”
   Takeo Fujii, Katsuya Suto
2. JST EIG CONCERT Japan " Organically Resilient and Secure Wireless Networks for Next-Generation IoT Technologies (ORACLE)"
   Koji Ishibashi
3. NICT B5G “Technologies for Next Generation Five Dimensional Mobile Infrastructures”
   Takeo Fujii, Katsuya Suto, Koya Sato

【Cooperative Research】

1. TIS Inc., Takeo Fujii, Katsuya Suto
2. NEC Corp. Takeo Fujii

2.2 Advanced Hardware Research Division

2.2.1 Purpose of Research

Research and development of wireless information/power transmission hardware for next generation mobile communication base stations and terminal devices

2.2.2 Research Staffs and Their Specialties

Prof. Koichiro Ishibashi	Low Power RF Devices, Sensor Networks
Prof. M. Matsuura	Wideband RoF Systems, Devices, Fibers and Integration
Prof. R. Ishikawa	Microwave/Millimeterwave Devices and Circuits
Prof. K.Wada	Microwave Filters and Their Applications
Visiting Prof.Y. Yamao	Reconfigurable RF Circuit, Nonlinear Compensation
Visiting Prof. K. Honjo	Microwave Engineering, Semiconductor Devices
Visiting Prof. Y. Takayama	Microwave Power Amplifier Systems
Visiting Prof. A. Saitou	Electro-Magnetic Wave Engineering, Antennas

2.2.3 Major Research Outcomes in 2022

（A） [Quasi-millimeter-wave wide-dynamic-range GaN HEMT outphasing amplifier]（Ishikawa Lab.）

In recent years, the greater sophistication and diversity in wireless communication systems have become remarkable, hence further improvements in performance of wireless transmitters in the base stations are required. Power amplifiers are an important device, which greatly affect distortions for signals and power consumption. A peak-to-average power ratio (PAPR) of recent digital wireless signals is large as more than 6 dB. A PAPR of 9 dB is often considered in 4G and 5G OFDM (Orthogonal Frequency Division Multiplexing) / QAM (Quadrature Amplitude Modulation) systems. In such systems, power efficiency at large output power back off levels dominates a total power consumption of the amplifiers than that in saturation levels. Thus, high efficiency characteristics are required for wide dynamic range in the amplifiers where a special attention should be paid on the efficiency at large output back-off (OBO) power level.

For this issue, we have developed a quasi-millimeter wave outphasing power amplifier constructing with two simple 50-ohm power amplifiers. For the power amplifier design to improve efficiency in the quasi-millimeter wave region, a trade-off between a devised circuit configuration and circuit insertion loss becomes a serious issue. The matching circuit of the 50-ohm power amplifiers for consisting to the outphasing power amplifier has to be carefully designed so that high efficiency is achieved with a low output power for a high input power, though the circuit is simple for loss reducing. For the fabricated outphasing amplifier with the GaN HEMT MMIC amplifiers designed at 28 GHz band, the dynamic range was maintained in the bandwidth of about 800 MHz, though there was room for improvement by the matching adjustment for the dynamic range (Fig. 2.2.1).

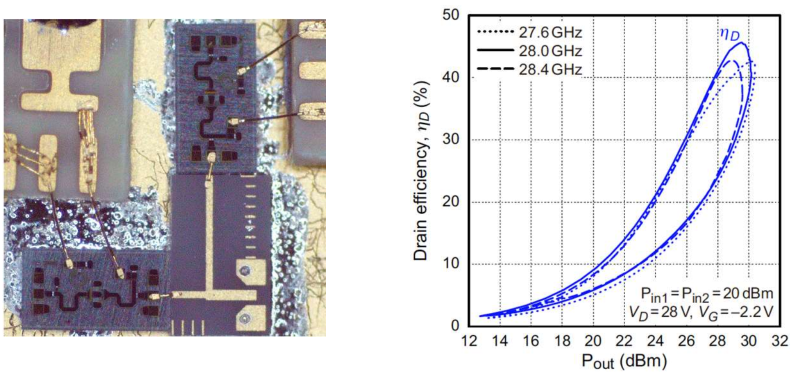


Fig. 2.2.1 Fabricated GaN HEMT outphasing power amplifier, and its characteristics

(B) [OAM Long-Range Communication by Changing Paraboloid Curvature and Feed Position] (Ishikawa Lab.)

We have demonstrated that the electro-magnetic wave propagation occurs with a single orbital angular momentum (OAM) mode when a current distribution of the azimuth angle ϕ-direction for a circular loop antenna conductor contains only one Fourier expansion coefficient. This condition almost retains at the loop-antenna conductor length of $n\lambda$ (n is the integer). As a common issue for the OAM communication, the directivity of the OAM waves is wide, especially for the loopantenna that has a small antenna aperture. Therefore, for a long-range communication, paraboloid reflectors are utilized for focusing the OAM waves Here, we have tried to optimize the curvature of the concave reflector so that the beam waist position of each mode of OAM waves becomes the same. In addition, a position relation among the feed points of the loop antennas was also optimized to improve a signal-to-interference ratio (SIR), based on the interference cancellation technique.

A 4-channel OAM multiplexing long-range communication test using loop antennas in the 12 GHz band was carried out. As a result, the worst-values of signal wave and SIR were improved by 6.5 dB and 9.9 dB, respectively, at 12.2 GHz and 70 cm long distance communication (Fig. 2.2.2).

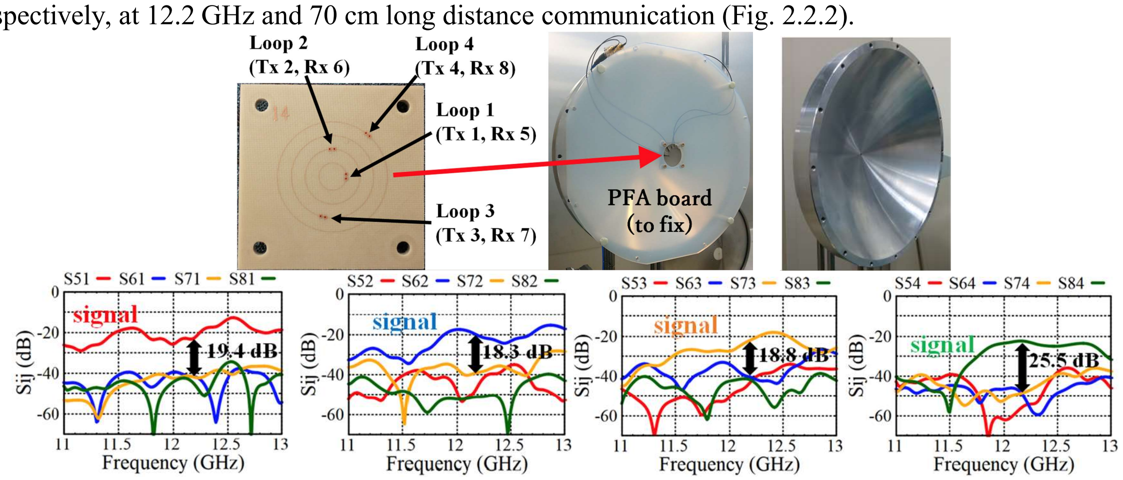


Fig. 2.2.2 Fabricated roop antenna systems, and its characteristics

(C) All-Optical Logic Gate in Semiconductor Optical Amplifiers (Matsuura Lab.)

In future data signal processing, it is important to realize integrated technologies that use the features of optical and electrical devices more efficiently. Logic gate is one of the essential functions, and there is a need for technology that can perform faster processing, as the speed of data processing increases. In the concept of photonic accelerator, more efficient data signal processing can be achieved by making full use of all-optical signal processing for logic gates that require high-speed processing and by using electrical signal processing to control multiple logic circuits.

Semiconductor optical amplifiers (SOAs), are key devices for all-optical signal processing and have many advantages such as small-foot print, low switching energy, and availability of monolithic integration, compared with other nonlinear devices. In particular, quantum-dot SOAs (QD-SOAs) provide higher gain, wider gain bandwidth, and faster gain recovery time than common SOAs, which have a great advantage in optical signal processing. For all-optical logic gates, several experimental demonstrations using SOAs and simulations using QD-SOAs have been reported.

In these devices, frequency chirp is a well-known phenomenon in which the carrier frequency changes instantaneously due to a change in the refractive index of the device as the light intensity changes.

In this year, we demonstrate an all-optical AND logic gate using filter-sliced frequency chirp in a QD-SOA. To effectively utilize frequency chirp, a probe signal sliced by a high roll-off optical filter is used before injecting into the QD-SOA. We also evaluate and compare the logic operations based on red and blue frequency chirp in the QD-SOA.

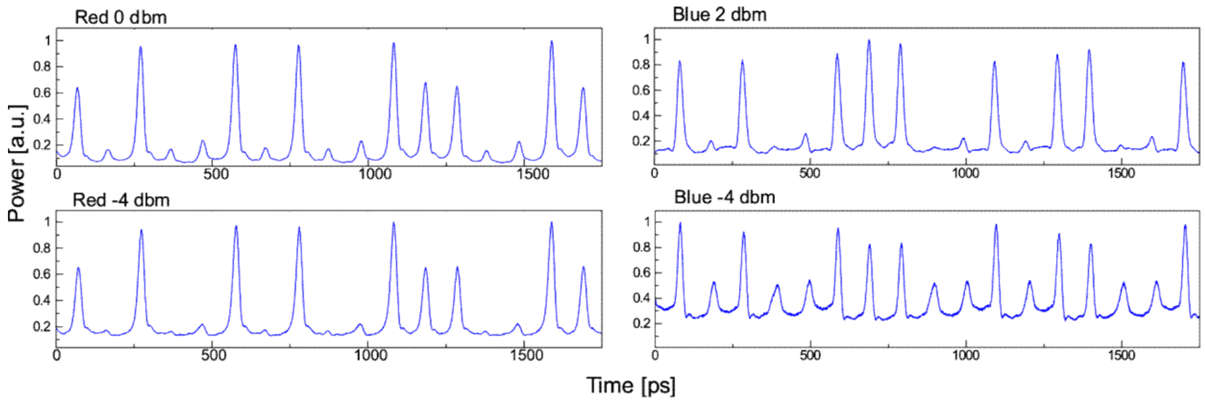


Fig. 2.2.3 Output signal waveforms of logic gates using (left) red and (right) blue frequency chirp while changing total input power.

Figure 2.2.3 shows the output signal waveforms of the logic gates using red and blue frequency chirp. In the case of red frequency chirp, it can be clearly seen that the output signal included patterning effect due to the gain recovery time even if the total power injected into the QD-SOA was changed. On the other hand, in the case of blue frequency chirp, there was no critical patterning effect of the output signal by adjusting the total power injected into the QD-SOA. In particular, when the total power injected into the QD-SOA was set to 2 dBm, the highest extinction ratio of 6.42 dB was obtained. In this setup, we also measured the bit-error-rate characteristics using a pseudo random bit sequence data, and the error-free operation of the output signal was successfully achieved. The obtained results showed that the logic gate using blue frequency chirp had higher performance than that of the logic gate using red frequency chirp.

2.2.4 Funds

【Grants-in-Aid for Scientific Research】

1. Grant-in-Aid for Scientific Research (C),"Microwave OAM Antenna" (A. Saitou)
2. Grant-in-Aid for Challenging Research (Exploratory) "Research on reconfigurable all-optical logic gates using semiconductor devices" (M. Matsuura)

【Commissioned Research】

1. MIC, SCOPE, "Research and development of reconfigurable OAM spatial multiplexing antenna technology for massive multiple access wireless networks" (R. Ishikawa, K. Honjo, A. Saitou)

【Cooperative Research】

1. SoftBank Group Corp. "Low power consumption amplifier" (R. Ishikawa)
2. ROHM Co., Ltd. "High frequency measurement technique for GaN-HEMT" (R. Ishikawa)
3. Fujikura Ltd. "High performance power amplifier for 5th generation mobile communication systems" (R. Ishikawa, Y. Yamao)
4. Japan Space Systems. "Technical evaluation of high-efficiency power transfer section related to "Research and development project for high efficiency wireless power transfer in space solar power systems" (R. Ishikawa)
5. Japan Space Systems. "Development of energy-related technology on the lunar surface (organization of technical issues related to electric power) Development and study of equipment, etc. for power transmission technology demonstration experiments from low-Earth orbit" (R. Ishikawa)
6. Japan Space Systems. "Study of RF amplifier for wireless power transmission in lunar orbit solar power generation system" (R. Ishikawa)

2.3 Division of Creating Advanced Wireless Systems

2.3.1 Purpose of Division

R&D of Advanced Wireless Systems and Networks contributing to development of society by sustainable technologies of wireless systems

2.3.2 Research Staffs and Their Specialties

Prof. Koji Ishibashi（Division Leader, Future NW, Distributed NW）
Prof. Takeo Fujii（Future NW, Cognitive Radio, Distributed NW）
Prof. Motoharu Matsuura（Future NW）
Prof. Celimuge Wu (Future NW, Distributed NW)
Associate Prof. Koichi Adachi (Future NW)
Associate Prof. Katsuya Suto (Future NW)

2.3.3 Major Research Results in 2022

[5D Spectrum Database] (Fujii Lab.)

In Beyond 5G/6G, non-terrestrial networks (NTNs) such as satellites and drones are expected to be used to expand the communication area, and frequency management in the height direction is required. In this study, we designed and developed a 5-dimensional (5D) spectrum database, which is an extension of the spectrum database of radio environment information studied in a 2-dimensional (2D) latitude and longitude plane to a 3-dimensional (3D) space including height information, and to 5D space including time and frequency. We report the details of the design and the results of the tests using experiments. The grid code of the designed 3D grid is described: As shown in Fig. 2.3-1, for the 2D grid code of latitude and longitude (2D grid code is an example of 10m grid), symbols indicating the grid size in the height direction are added based on the height of 0 m (E1:1m, E2:2m, E5:5m, E10:10m). In addition, "+" is added for points higher than 0 m in elevation and "-" is added for points lower than 0 m in elevation. A numeric value indicating the grid number based on 0 m elevation is added after the above codes. By appropriately adding symbols, codes, and numeric values to the 2D grid code in this way, it is possible to express the elevation range in any height grid for a 2D grid code of a particular parcel. We report the results of a test of the database developed on the basis of the above design. In this test, radio maps were generated based on the measurement data obtained from an actual experiment, which was extended to a 3D grid in the height direction and statistically analyzed. The data used in the test was obtained from an experiment conducted on February 15, 2022. The experiment was conducted on signals in the local 5G Sub-6 band (4.8 GHz band) operated by Ehime CATV in Ehime, Japan. As statistical processing parameters, we specified a 2D grid size of 10 m for latitude and longitude and a grid size of 10 m for height direction (elevation), and generated radio maps by averaging the data for each 3D grid, which is a 10 m cube. Fig. 2.3-2 shows the generated radio maps. In this figure, the 3D grid is divided into elevations in 10 m increments and shown as 2D radio maps. For the present measurement data, three radio maps were generated for elevations ranging from 40 to 49.999 m, 50 to 59.999 m, and 60 to 69.999 m. Without elevation gridding, the radio map is shown in the lower right corner of Fig. 2.3-2, and this map is the sum of each map divided by elevation. From the above, we have confirmed that the developed database enables the recognition of radio space that reflects the actual 3D space.

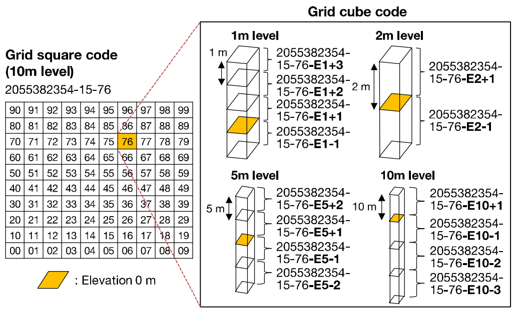


Fig. 2.3-1. Example of 3D grid codes with added heigh direction.

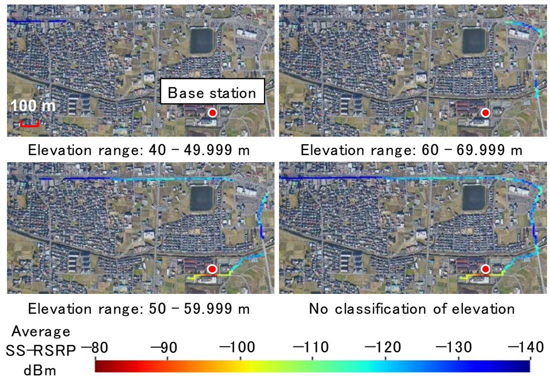


Fig. 2.3-2. Radio maps generated for each 10m elevation range.

[REM Construction Method under Threatening Environment (Fujii Lab.)

Cognitive radio (CR) is a wireless communication technology that has emerged as a promising solution to address the spectrum scarcity problem by enabling dynamic spectrum access (DSA). It allows unlicensed users to opportunistically access the licensed spectrum when it is not in use by licensed users. Cognitive radio networks (CRNs) rely on intelligent algorithms to sense the spectrum environment, detect available frequencies, and optimize the use of the spectrum. However, accurate knowledge of the radio environment is crucial for efficient spectrum management. This has led to the development of the Radio Environment Map (REM), which provides a comprehensive representation of the radio environment. The REM enables cognitive radios to make informed decisions on spectrum access, leading to efficient spectrum utilization and increased network capacity.

However, the open condition may lead some threats for the REM construction. In our study, we consider about when the malicious terminals exist in the environment and rewrite the sensed information and send false information to the database in order to lead a big error to the REM. If we do interference analysis or channel allocation based on such map, it might ruin the CRNs.

In order to deal with such condition, we proposed a Kriging-based Trust Nodes Aided REM construction system. By adding small amount of the trust node, the system can evaluate real-time comparisons and accumulative total reputations to select reliable datasets for constructing the REM in a threatening environment. Fig. 2.3-3 shown our proposed system. As Fig. 2.3-4 shown is the ground truth REM, the Fig. 2.3-5 is the map under the attacks, Fig 2.3-6 is the map adapted with our proposed algorithm. The proposed method achieves high map accuracy by monitoring the cumulative behavior of even a small number of participants.

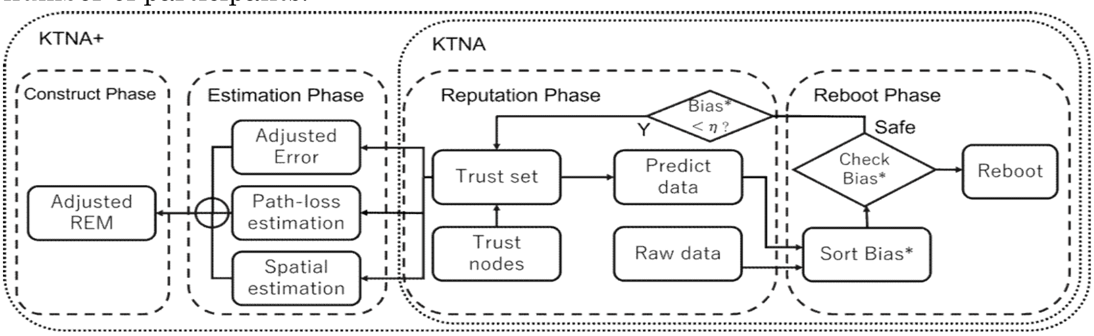


Fig. 2.3-3 Kriging-based Trust Nodes Aided REM Construction System

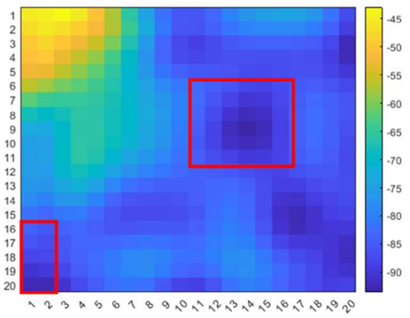


Fig. 2.3-4 Ground truth

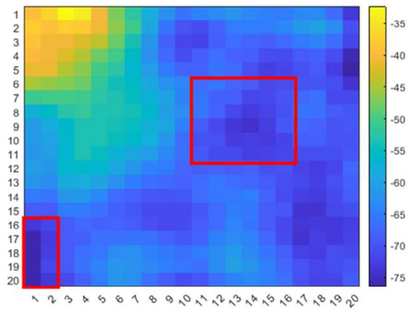


Fig.2.3-5 Under attacking

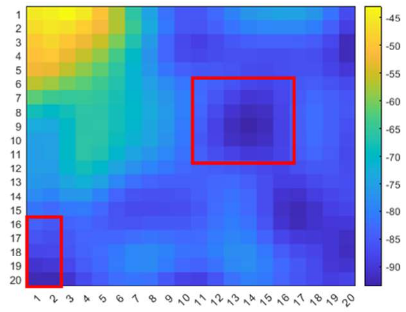


Fig.2.3-6 Proposed method

[Method of Constructing Measurement-based Spectrum Database for Non-Terrestrial Network] (Fujii Lab.)

Due to the popularization of the Internet and the increase in smart devices, effective use of frequency bands is required. To solve this problem, non-terrestrial networks (NTNs) such as satellites have been attracting attention (shown in Fig. 2.3-7). NTNs are affected by blocking vegetation and buildings on land and changes in positional relationships by using existing radio propagation models, making it difficult to predict the radio environment.

The measurement-based spectrum database collects radio environment data such as frequencies, received power, and location information collected by a group of ground terminals. Thus, it is not possible to statistically process the measurement data at the receiving position. Due to the constant movement of satellites, the received signal strength intensity with time. Thus, it is not possible to statistically process the measurement data at the receiving position.

Therefore, we propose a method of statistically processing measurement positions and satellite positions by grid them using a celestial coordinate system that can grasp the angular relationship between measurement points and satellites.

Furthermore, actual measurements of GPS satellites were carried out in an environment where radio wave blocking may occur, and the division angle in the sky was examined based on the measurement data. Measurement data includes elevation and azimuth angle of the satellite and the Carrier-to-Noise Ratio: CNR (i.e., received signal strength) data.

We focused the CNR data in which the range of azimuth angle is fixed at 166° to 208° (i.e., angle expected to be in non-line of sight (NLOS)), and then the range of elevation angle is 0° to 20° (angle expected to be in NLOS) and 20° to 30° (angle expected to be in line of sight (LOS)). Based on that CNR data, the average value of the CNR for each elevation angle when the range of elevation angle is 0° to 30° was calculated. The result is shown in Fig. 2.3-8. It can be read that the variance of the CNR tends to increase when the elevation angle changes from the NLOS state to the LOS state around 19°. Also, we calculated the variance of the CNR for each division angle in the elevation direction. As a result, we found the finer the division angle, the smaller the variance of the CNR tends to be.

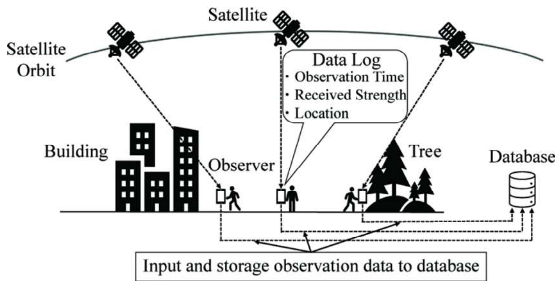


Fig. 2.3-7. Image of measurement-based spectrum database for NTNs.

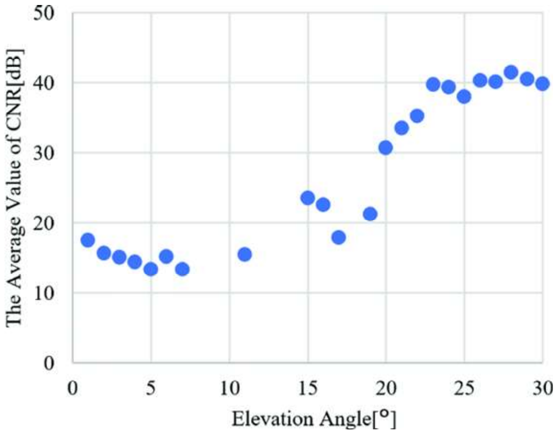


Fig. 2.3-8. The result of the average value of CNR

[Grant-Free Access for Massive Users] (Koji Ishibashi Lab.)

Future wireless communication such as Beyond 5G and 6G would accommodate a massive number of devices, as represented by Internet-of-Things (IoT). In order to realize efficient low-latency data transmission of a massive number of devices, designing multiple access schemes is crucial. As one of the promising techniques, grant-free non-orthogonal multiple access (GF-NOMA) has been actively studied. The base station (BS) does not exclusively assign radio resources to active users for data transmission in GF-NOMA, as shown in Fig. 2.3-9. This academic year, we have proposed a GF-NOMA scheme based on orthogonal frequency division multiplexing (OFDM) considering an implementation issue such as carrier frequency offset (CFO). In this scheme, a multi-antenna BS estimates the active users, channel coefficients, and CFOs using the overlapped pilot signals spread over both the time and frequency domain. It is performed via a multiple measurement vector approximate message passing (MMV-AMP) with space-alternating generalized expectation-maximization (SAGE)-based CFO update. Fig. 2.3-10 shows the activity error rate (AER) performance of GF-NOMA with the proposed algorithm. In this figure, MMV-AMP performance ignoring the effect of CFOs is plotted as a green chain line with triangle markers. The proposed scheme and MMV-AMP performance with perfect knowledge of CFOs are plotted as a red solid line with circular markers and a blue dotted line, respectively. From the figure, the performance of our proposed scheme is comparable to MMV-AMP with perfect knowledge of CFOs, while the performance of MMV-AMP ignoring CFOs draws a high error floor.

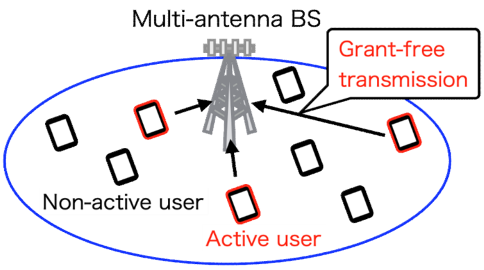


Fig. 2.3-9 GF-NOMA system

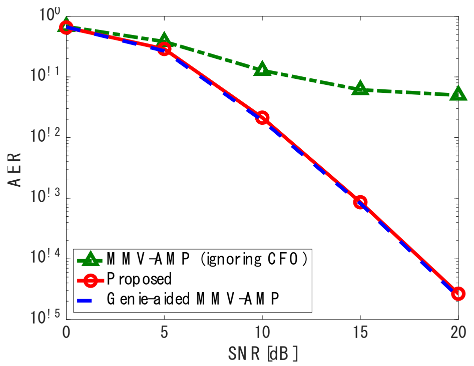


Fig. 2.3-10 Activity error rate of the proposed GF-NOMA.

[Beamforming Design for Cell -Free Massive MIMO Systems] (Koji Ishibashi Lab.)

Network-assisted full-duplex (NAFD) cell-free (CF) massive multiple-input multiple-output (mMIMO) over millimeter wave channels is expected to be an enabler of 6G systems. NAFD CF-mMIMO can accommodate uplink and downlink users simulateneously, as illustrated in Fig 2.3-11, and increases spectral efficiency dramatically. However, this simultaneous transmission causes strong inter-user equipment (UE) and inter-access point (AP) interference. To mitigate inter-UE interference, the estimation of channels among UEs is essential while this estimation is practically difficult, considering the required overhead. Hence, considering the characteristic of millimeterwave channels, we proposed the inter-UE channel estimation method using geographycal information of UEs and proposed AP allocation and beamforming design method for mmWave NAFD CF-mMIMO. Figure 2.3-12 depicts average throughput with the different number of UEs. Besides our proposed method, SotA with perfect channel state information (CSI) or without inter-UE CSI, and time division duplex (TDD) are considered as competitors. SotA with perfect CSI outperforms the proposed method while SotA without inter-UE CSI exhibits the worst performance. Although our proposed method do not assume perfect CSI, it can mitigate the inter-UE interference effectively and achieves the performance close to the SotA with perfect CSI. Moreover, the comparison with “TDD” reveals the effectiveness of NAFD.

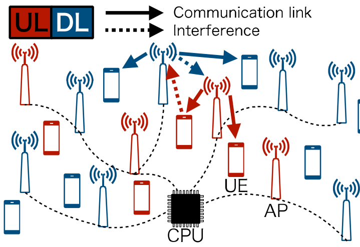


Fig. 2.3-11 System model of NAFD millimeter-wave cell-free massive MIMO systems.

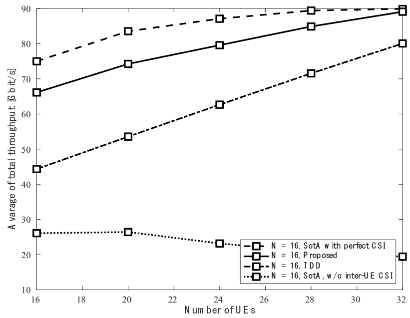


Fig. 2.3-12 CDF of achievable throughput of CSI knowledge with the different number of UEs.

[Robust Beamforming Design for Millimeter-Wave Channels] (Koji Ishibashi Lab.)

Millimeter-wave (mmWave) communications are expected to be foundations of beyond 5G and 6G wireless architectures. Recently, various blockage prediction methods and several coordinated multi-point (CoMP) transmission methods exploiting blockage information have been proposed to overcome the vulnerability of mmWave signals, as shown in Fig 2.3-13. However, these methods considered only single-carrier narrowband channels, which are not appropriate for practical mmWave systems. MmWave systems usually employ orthogonal frequency division multiplexing (OFDM) to mitigate the effect of frequency selectivity caused by the large bandwidth. To this end, we proposed a new robust CoMP transmission scheme against random path blockages and designed to minimize the outage probability of users. Figure 2.3-14 shows the achievable throughput of proposed and state-of-the-art approaches. In this figure, sum rate maximization (SRM)-based CoMP with the knowledge of instantaneous blockage was plotted as a solid curve. Conventional and proposed outage minimization (OutMin)-based CoMP with blockage

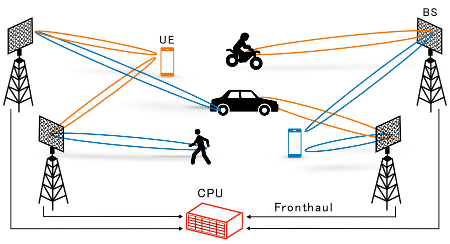


Fig. 2.3-13 System model of CoMP millimeter-wave communications with random blockages.

probability were denoted by a solid line with "+" markers and a dashed line, respectively. The comparison between the proposed OutMin and conventional OutMin indicates the gain obtained by the proposed joint design of beamforming and power and data rate allocation. Furthermore, even though SRM-based CoMP ideally exploits the available channels during the data transmission, the proposed OutMin-based CoMP approaches the performance up to target rates of 16 [Mbps] only with path blockage probabilities.

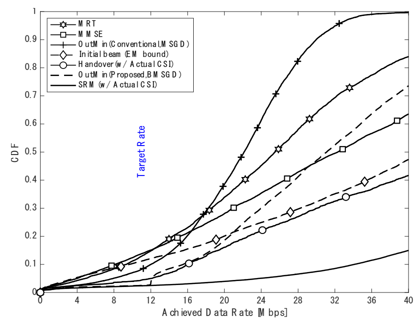


Fig. 2.3-14 CDF of achievable throughput of blockage-robust approaches.

[Optically Powered Transmission Systems for Optical Access Networks]（Matsuura Lab）

In future mobile communications, radio-over-fiber (RoF) that transmits radio-frequency (RF) signals into optical fibers will be one of the key technologies. In order to increase the speed and the capacity of mobile communications, the use of higher RF signals and a large number of remote antenna units (RAUs) are needed. In such systems, how to supply power to a large number of RAUs will be an important issue in future RoF networks.

To drive an RAU without any external power supply, an electrical power of 10 W or more has to be delivered by power-over-fiber (PWoF). To achieve this, we have proposed a PWoF using a double-clad fiber (DCF), which compose a single-mode (SM) core for signal transmission and the surrounded inner cladding for power transmission. On the other hand, in these experiments, the wavelength of feed light was 808 nm, and the power transmission efficiency was not very high, which limited the efficiency for long-distance transmission. To solve this problem, we have been investigating and studying the suitable feed light wavelength and the DCF. In particular, DCFs with pure silica inner cladding have been shown to provide low-loss power transmission band at 1550 nm. However, the DCF required a different coupling method between feed light and data signal unlike conventional DCFs, and it was difficult to obtain high transmission performances of the data signal under high-power feeding.

To improve the power transmission efficiency of PWoF using DCFs, we present a novel scheme for a DCF, which has pure-silica inner cladding, with low-loss transmission and

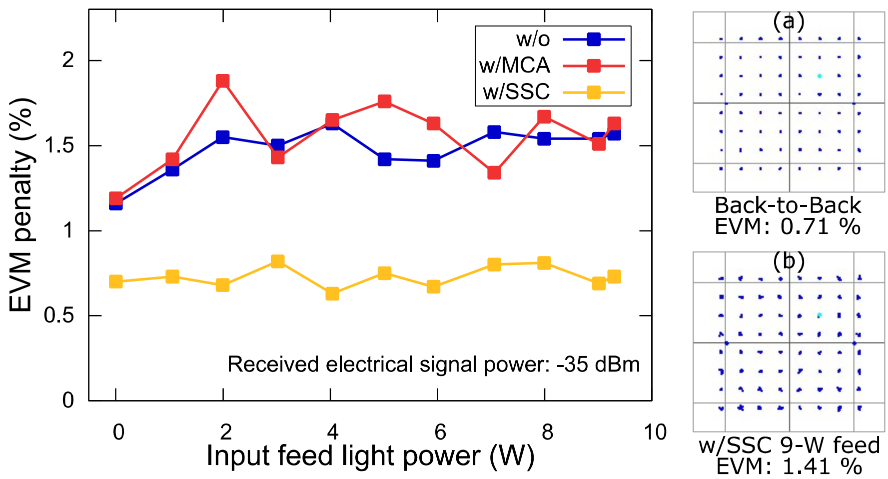


Fig. 2.3-15 EVM penalties of transmitted RoF data signals. Insets show constellations of (a) back-to-back and (b) transmitted RoF signals using SSC when feed light power was 9 W.

demonstrate a simultaneous data and power transmission at 1550 nm. As a result, we successfully achieve not only improvement of the power transmission efficiency, but also high transmission performance of the simultaneously transmitted RoF data signals.

Figure 2.3-15 shows the EMV penalties to the back-to-back signal of the transmitted RoF data signals while changing the input feed light power. When the spot-size converter (SSC) was not used (without and with mode-conditioning fiber (MCF)), the EVM penalties was increased over 1%. This was due to the fact that a portion of the RoF data signal experienced multi-mode transmission, which gave rise to mode dispersion and the effect of crosstalk with the feed light. On the other hand, when the SSC was used, the EVM penalty was less than 0.6%, and there was no significant increase even if the feed light power was increased. This result shows that the use of SSC enables not only to provide nearly single-mode propagation of the RoF data signal, but also to avoid the crosstalk between the feed light and RoF data signal.

[Fuzzy Logic based Client Selection for Federated Learning in Vehicular Networks] (Celimuge Wu Lab.)

Federated learning (FL) is a promising paradigm for achieving distributed intelligence by protecting user privacy in vehicular networks. Considering limited computing and communication resources, it is important to select appropriate clients from a huge number of users to participate in the training process. In vehicular networks, the problem of choosing proper clients is particularly complex due to the heterogeneity of network users, including the differences in the data, computation capability, available throughput, and samples freshness. We design a fuzzy logic based client selection scheme to address this issue. The proposed scheme considers the number of local data, computing capability, and network resources of each client participating in FL based on fuzzy logic. In addition to realistic computer simulations, we also design a prototype system (Fig. 2.3-16 left), where Raspberry Pi and laptops are used as FL clients, and verify the superiority of the proposed method through extensive experiments (Fig. 2.3-16 right). As shown in the experimental results, the proposed scheme is able to improve the accuracy of FL significantly as compared with the baselines.

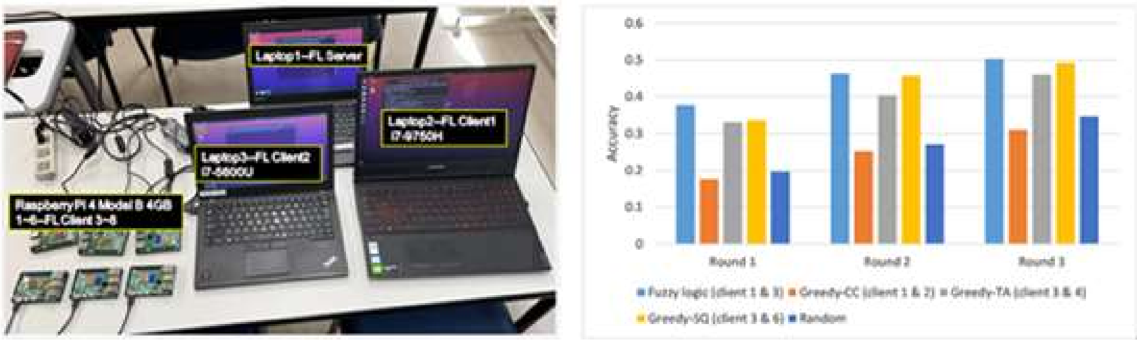


Fig. 2.3-16 Client Selection for FL (left: prototype system; right:. accuracy comparison between the proposed scheme and other baselines).

2.3.4 Funds

【Grants-in-Aid for Scientific Research】

1. Scientific Research B “Establishment of Cell-Free Network Architecture for User-Centric Communications”
   Koji Ishibashi
2. Scientific Research Fostering Joint International Research Type B “Simultaneous

Wireless Information and Power Transfer with Intelligent Reflecting Surface”
Katsuya Suto
3. Scientific Research B “Sensor Networks with High Speed Environmental Adaptation by Recognition of Synthesizing Wave”
Takeo Fujii (PI belongs to other organization)
4. Scientific Research B “Quantum Optimization Accelerating High-Speed, High-Capacity Wireless Communications”
Koji Ishibashi (PI belongs to other organization)

【Commissioned Research】

1. MIC “Highly-Reliable Wireless Access Technology for Advanced 5G Networks”
Koji Ishibashi
2. MIC SCOPE “Flexible LPWA Based on Environmental Dynamics”
Koichi Adachi, Takeo Fujii
3. NICT B5G “Technologies for Next Generation Five Dimensional Mobile Infrastructures”
Takeo Fujii, Katsuya Suto, Koya Sato
4. MIC “Research and development of advanced optical transmission technology that contributes to a green society”
Motoharu Matsuura
5. NICT B5G “Construction of a highly efficient wireless communication system using high power radio-over-fiber transmission”
Motoharu Matsuura
6. NICT JUNO3 “End-to-end network slicing and orchestration in future programmable converged wireless-optical networks”
Motoharu Matsuura

【Cooperative Research】
1. KDDI Research Inc., Motoharu Matsuura
2. NEC Corporation, Takeo Fujii
3. KDDI Research Inc., Koji Ishibashi
4. Ericsson AB, Koji Ishibashi
5. Softbank Corporation, Takeo Fujii
6. Toyota Motor Corporation, Celimuge Wu

2.4 Division of Exploring Low Power Wireless

2.4.1 Purpose of Division

This division is aiming at low power wireless device technologies and application systems, which become fundamentals for future wireless communication systems. We are investigating such low power wireless technologies as super low power LSI design, energy harvesting technology, power transfer technology by optical fiber, as well as low power networks by theoretical approach. We also create new wireless application systems using the low power wireless technologies.

2.4.2 Research Staffs and Their Specialties

Prof. Koichiro Ishibashi (Head of Division, Low-power devices)
Prof. Motoharu Matsuura (Radio over Fiber)
Prof. Takeo Fujii (Smart meters)
Prof. Koji Ishibashi (Green network and communication theory)
Prof. Ryo Ishikawa (RF energy harvesting)
Associate Professor, Koichi Adachi (LPWA)

2.4.3 Major Research Outcomes in 2022

[Development of Energy Saving Lighting System using Illumination Beat Sensor (Koichiro Ishibashi Lab, Adachi Lab)

A new approach to reduce energy of LED lighting system using Illumination Beat Sensors is proposed. The sensor is 8g weight and small size totally within credit card size in area and operates without battery and transmits illumination data to a luminaire by ID signal interval time, so that the sensor can be placed anywhere and semi-permanently operates. By making the lighting system using the Illumination Beat Sensors, total energy of lighting system can be reduced by 43%. This lighting system can address issue of energy shortage and carbon zero - emission for the lighting systems anywhere in such places as houses, buildings, factories and so on.

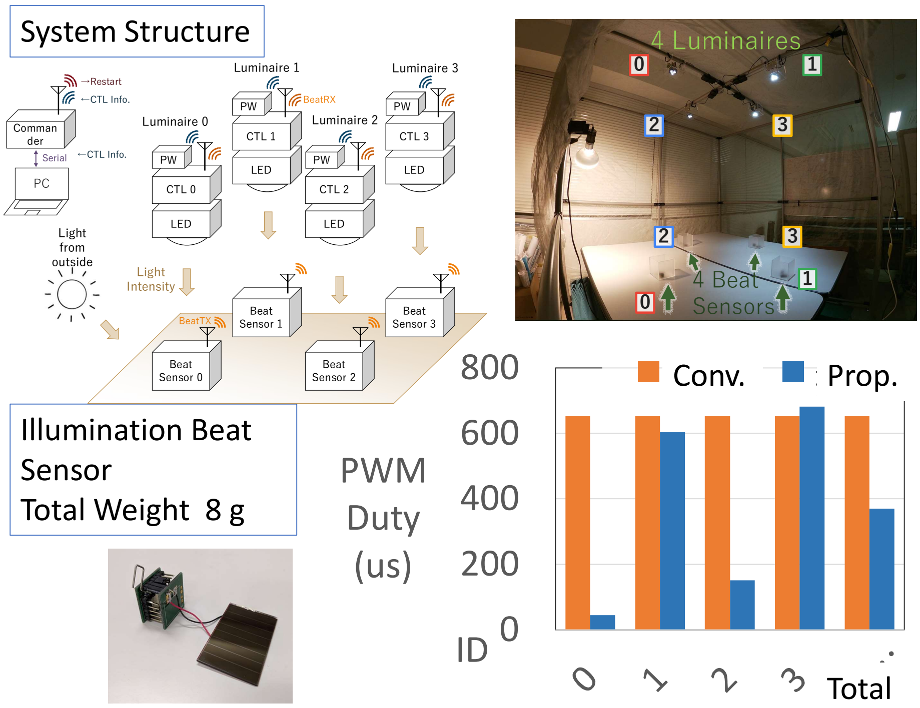


Fig. 2.4-1 Energy saving lighting system, Illumination Beat Sensor, and Effect of the energy saving depending on the system.

[Optically Powered Drone for Airborne Base Stations] (Matsuura Lab.)

Mobile communication services are crucial during emergency disasters and temporary events and future mobile communication systems should be able to provide such services. Airborne base stations using drones are highly effective as stand-in base stations in areas where the ground base stations are inoperable or at temporary event sites. However, it is difficult for conventional drones to provide mobile communication services without interruption due to flight time limitations caused by their limited battery capacity. Thus, a drone drive with a non-interrupted power supply is urgently needed.

In this year, we developed an airborne base station that enables drones to be driven and maneuvered by optical fibers. We simultaneously transmitted radio frequency (RF) data signals for the airborne base station and control signals for the drone and evaluated the transmission performances of the RF signals and the controllability of the drone. Furthermore, we conducted a flight experiment on a medium-sized drone powered by optical fibers.

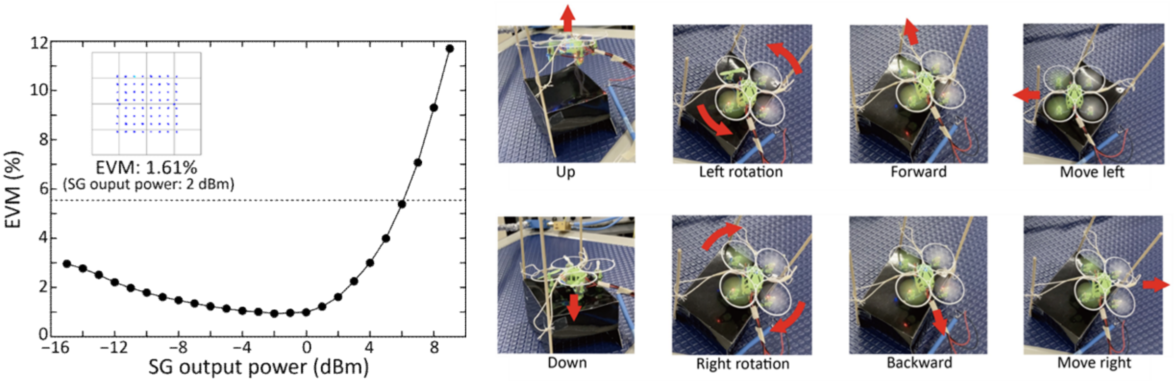


Fig. 2.4-2 (a) EVM as a function of SG output power. Dashed line shows EVM of 5.6%. Inset shows constellation of transmitted RF data signal when SG output power was 2 dBm. (b) Photographs illustrating control of optically controlled drone. Red arrows indicate direction in which the drone is moving.

For a detailed evaluation of the transmission performance of the RF data signal, the error-vector magnitude (EVM) of the transmitted signal was measured; the results are shown in the left side of Fig. 2.4-2 (a). The dashed line shows an EVM of 5.6%, which is necessary to ensure adequate received signal quality for the modulation format used. The inset shows the constellation of the transmitted RF data signal when the signal generator (SG) output power was 2 dBm. As the SG output power increases above 0 dBm, the EVM value also increases. This was due to the nonlinear distortion caused by the excessive electrical power input to the laser-diode. However, as the SG output power decreased below 0 dBm, the EVM slowly increased. This indicates signal quality degradation due to the weakening of the signal component. In contrast, the EVM was below 5.6% over a very wide power range, indicating that the received RF data signal had high signal quality. The results indicate that the signal transmitted to the drone has a sufficient signal quality to be radiated from the airborne base station.

In order to verify whether the control signals are accurately transmitted by the RoF transmission, we conducted drone control tests based on the experimental setup. By using the RF-absorbing sheet, we controlled the drone by radio-over-fiber (RoF) transmission using a 100 m standard single-mode fiber (SSMF). Photographs illustrating drone control are shown in the right side of Fig. 2.4-2 (b). We confirmed the operability of the drone via the remote controller (RC) controller by performing eight different control operations, wherein the drone initiated pairing operations through RoF transmission. This shows that the drone can be operated using an optical fiber, even without wireless communication.

[Spectrum Sharing for LPWA Under Intra-system and Inter-system Interference Constraints] (Fujii Lab.)

Nowadays, depletion of frequency resources has been expected because of a huge number of low power wide area (LPWA) nodes. Despite this, various LPWA systems with different communication protocols have been developed according to use cases (e.g., long range wide area network (LoRaWAN) and wireless smart utility network (Wi-SUN)), utilizing the same unlicensed Sub-GHz bands. In addition, when many LPWA nodes start to transmit observation information to gateway (GW), the nodes randomly determine their transmission timings and frequency channels regardless of the channel occupancy conditions. Therefore, the intra-system and inter-system interferences on the same band may frequently occur at an arbitrary system's GW, which may deteriorate the signal demodulation performance in the same system.

Thus, we aim to guarantee the demodulation performance under the intra-system and inter-system interference constraints. We propose successive interference cancellation (SIC) based on cooperation between multiple GWs among multiple LPWA systems. Fig. 2.4-3 shows the system model. First, the GW which succeeds in demodulating shares the obtained binary sequence and received waveform to the GW with failing it. Then, the failing GW removes the signal by adaptive filtering and fast Fourier transform.

Fig. 2.4-4 shows the average PER as a function of SNR with assumption of time synchronization, in which the two LoRa signals (L1 and L2) and one Wi-SUN signal (W1) are superposed with equal received power. The black line indicates the average PER when the single GW can demodulate only the same system's signals. The blue and red lines indicate the average PER when performing SIC at a single GW and between multiple GWs, respectively. From the black line in Fig. 2.4-4, it is confirmed that a single GW cannot demodulate 'L2'. Accordingly, it is shown that 'L2' (or 'L1') cannot be subtracted accurately as in blue line. In contrast, it can be confirmed that our proposed method achieves suppression for 'L2' and 'W1' because shared 'L1' can be accurately subtracted.

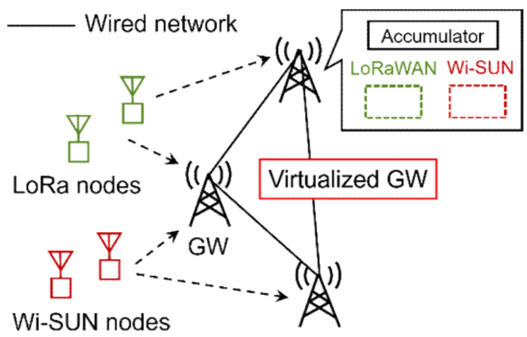


Fig. 2.4-3. System model.

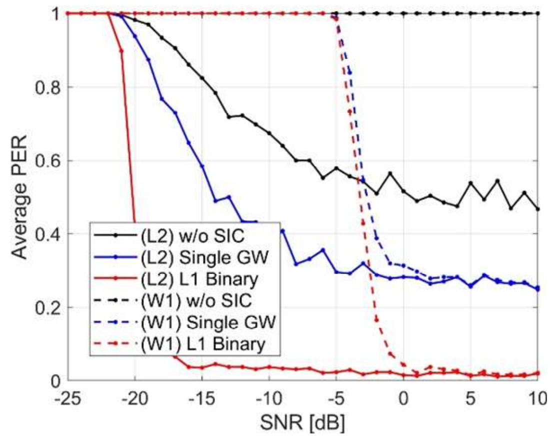


Fig. 2.4-4. Average PER as a function of SNR (w/o time synchronization, {L1, L2, W1}).

[Packet Transmission Considering Duty-cycle Based on Packet-Level Index Modulation for LoRaWAN] (Fujii Lab.)

In LoRa transmission system, the transmittable time of each channel is limited by duty cycle (DC). To increase the amount of data can be transmitted under this constraint, packet-level index modulation (PLIM) has been proposed. PLIM assigns a channel index (CI) and a time slot index (TSI) to the frequency channel and the divided time slot, respectively. The time slot and channel for transmitting packet is selected based on the transmitted data sequence. This allows additional information to be transmitted by CI and TSI. However, if the transmitted bit string is biased, the selected transmission channel will also be biased, thus reducing the amount of data that can be transmitted compared to conventional LoRa transmission due to the DC constraints described above. This paper proposes an adaptive CI exchange method when the occurred CI is biased.

Fig. 2.45. shows the system model for this simulation. In this study, each terminal sends packets using PLIM and makes CI exchange decisions at regular intervals based on the recorded channel history. The CI exchange decision predicts the transmission time ratio of each channel based on the packet transmission channel history. The predicted values of each channel are compared, and if the maximum difference among all channel pairs exceeds a threshold value, CI exchange is performed on that channel pair.

To evaluate the performance of the proposed method, computer simulations were executed using the C language. For the bias of the transmitted bit sequence, the packet loss ratio by DC for each of the conventional PLIM and the proposed method is shown in Fig. 2.4-6. Simulation results confirm that the number of packets that become untransmittable at the DC can be reduced.

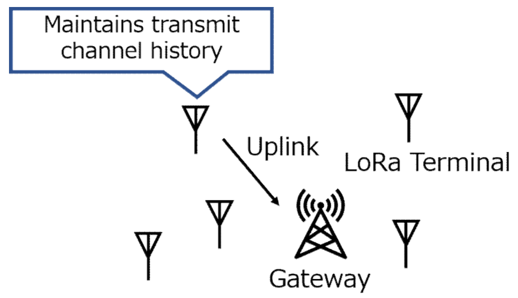


Fig. 2.4-5. System model

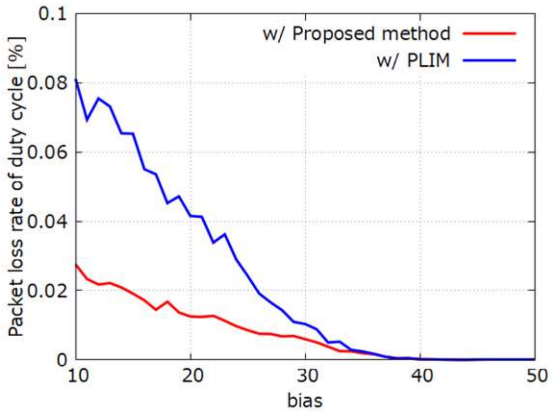
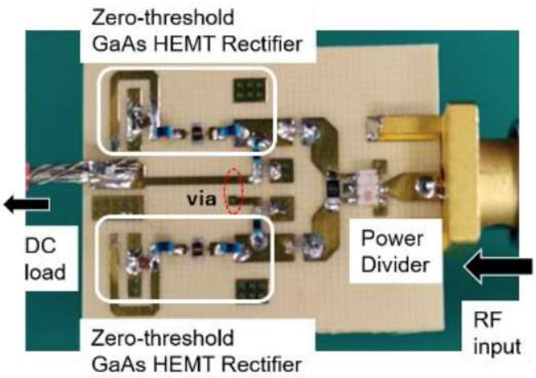


Fig. 2.4-6. Packet loss rate of DC

[DC voltage synthesis of 2.45-GHz-band sub-mW high-efficiency rectifier using zero-threshold GaAs HEMTs] (Ishikawa Lab.)

In order to obtain a sufficient DC output voltage, a DC voltage synthesis configuration has been developed by using sub-mW-class high-efficiency zero-threshold GaAs HEMT rectifiers at 2.45-GHz band. A sub-mW-class high-efficiency rectifier has been successfully realized based on a resonance control technique on a small-signal condition. In addition, a cold-start operation is also realized by using a zero-threshold GaAs HEMT. By connecting the DC output ports of the GaAs HEMT rectifiers in series, a DC output voltage synthesis rectifier has been constructed. The fabricated GaAs HEMT rectifier exhibited an equivalent RF-to-DC power conversion efficiency of 67% and a DC output voltage of 2.1 V at each input power of 0 dBm (Fig. 2.4-7).



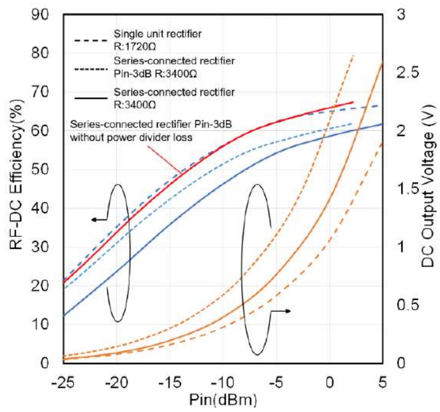


Fig. 2.4-7 Fabricated GaAs HEMT rectifier, and its characteristic

[Encryption-then-Compression Technique for Practical Systems] (Koji Ishibashi Lab.)

Wireless sensor networks (WSNs) have to meet low-power consumption and private data security via encryption. To satisfy these requirements, encryption-then-compression (EtC) has been studied. Conventional EtC systems assume that bits in packets follow a Bernoulli distribution. However, in practical WSNs system, the source data has a specific structure such as date, time, and user idendifier. In addition to the data structure, these data are regularly based on alphanumeric coding system such as ASCII. Hence, practical data packets do not follow theoretical Bernoulli distribution, and this gap between theory and practice would cause the performance degradation of EtC systems. In this academic year, we have proposed a realistic EtC scheme, considering the ASCII coding and specific packet structure. Fig. 2.4-8 shows the decoding performance of the proposed EtC scheme wher the data packets were obitaned by smart meters in operation. The results show that our proposed method can compress the packet length by almost half while the convetional one could not compress the encrypted packets.

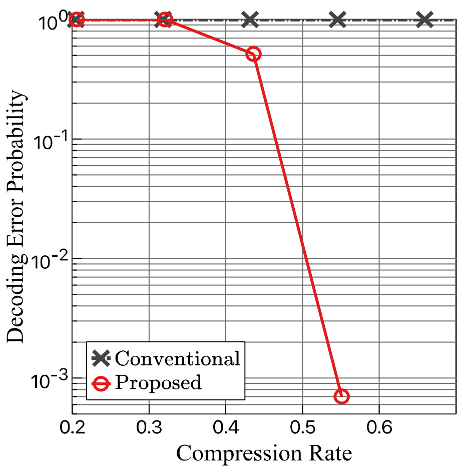


Fig. 2.4-8 Decoding performance

[Packet-Level Index Modulation for LoRaWAN] (Adachi Lab.)

To overcome the limitation of data rate of low power wide area network (LPWAN), packet-level index modulation (PLIM) has been proposed. In addition to the payload in the data packet, additional bit sequences can be transmitted through time slot and frequency channel selection. However, due to the inexpensive hardware of LPWAN, the clock speed between an end node (EN) and a gateway (GW) differ from each other. This difference results in time slot misdetection of PLIM. We have previously proposed a clock drift estimation and compensation for PLIM and implemented in commercially available LoRaWAN systems. LoRa mini-JP and Dragino LG308 are used as EN and GW, respectively. The functionalities are implemented by the LMiC library and OpenWrt. The data flow considered in this experiment is shown in Fig. 2.4-9. Each terminal obtains the temperature every 1 min and sends the obtained data to the GW using PLIM. Once the GW receives the data, it estimates and compensates for the clock drift and detects the time slot and frequency channel to decode the PLIM bit sequence. Then, the GW transfers the decoded PLIM sequence to the server via the MQTT protocol. The developed system has functionalities to adaptively change LoRa

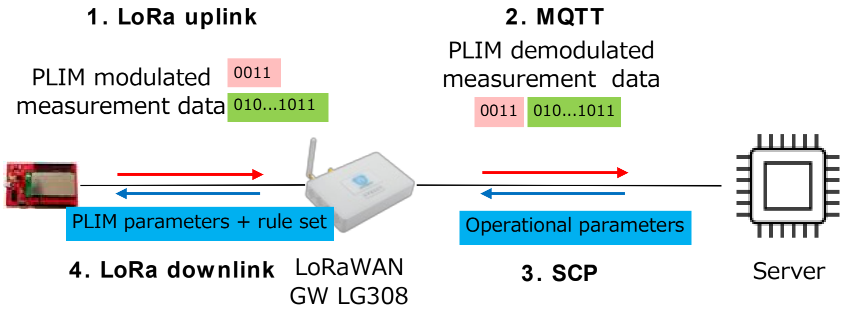
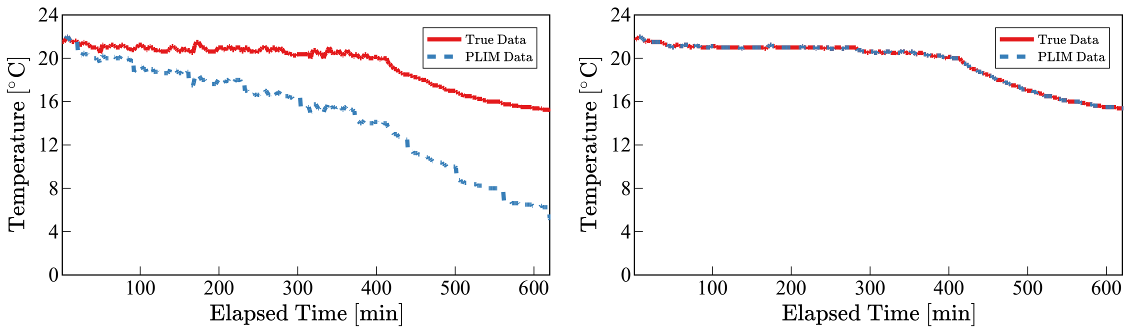


Fig. 2.4-9. Data flow



(a) w/o compensation (b) with compensation

Fig. 2.4-10. Experimental results

transmission parameters such as information collection intervals and available frequency channels. Fig. 2.4-10 shows the experimental results. The time slot length is set to 1 [sec], and each EN transmits its data packet by selecting one of the combinations with 8 frequency channels and 32 time slots. Thus, PLIM can convey additional 8 bits. In the experiment, 5 bits are used for representing integer numbers and the remaining 3 bits are for decimal numbers. As can be seen from the figure, time slot misdetection occurs as time elapses if the proposed method is not adopted and results in error. On the other hand, the proposed

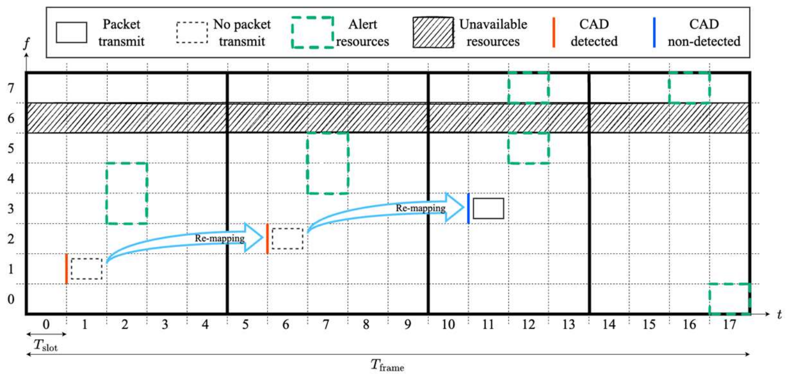


Fig. 2.4-11. CAD-based PLIM with enhanced index mapping

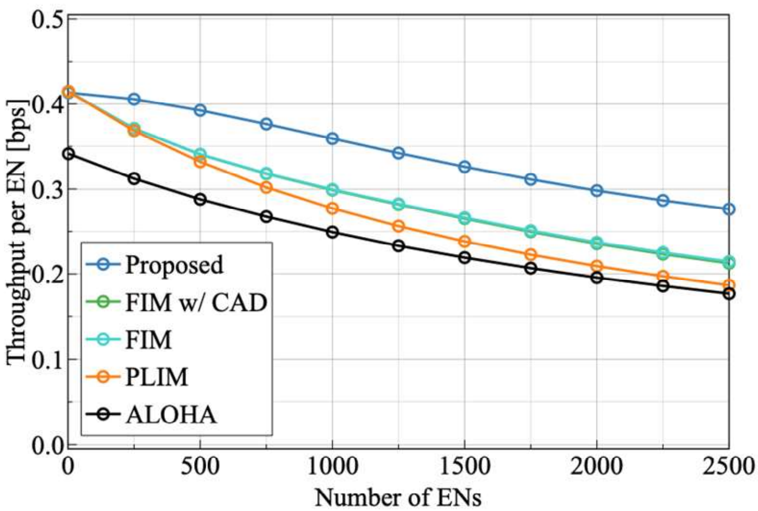


Fig. 2.4-12. Throughput performance

method achieves accurate time slot detection.

Last year, we proposed a flexible index mapping (FIM) that flexibly changes the mapping between the frequency-time slot index and bit sequence. However, in PLIM with flexible index mapping (FIM), an EN must discard the data packet if the EN cannot use the selected frequency-time slot resource. Thus, the system throughput performance degrades when many ENs exist in the system. To overcome such shortcomings, we have proposed an improved version of FIM, where each EN divides a transmission frame into several subframes and performs channel activity detection (CAD) in each subframe. Doing so can improve the transmission opportunity compared to the original FIM. To be specific, as Fig. 2.4-11 shows, the available resources of R are divided into subframe of $V(d)$. Then, PLIM bit sequence is expressed by the resource within each subframe. Here, $V(d)$ is the number of frame division that is uniquely determined by frame division index d.

Each EN selects one transmission resource based on the PLIM bit sequence and performs CAD at the starting time of the selected resource. If the EN does not detect any signal the EN transmits a data packet. On the other hand, if it detects any signal, it reperforms resource selection and CAD in the subsequent subframe. If the EN detects the ongoing transmission, the EN repeats this procedure until the end of corresponding frame. Simulation results (Fig. 2.4-12) have shown that the proposed method can increase the throughput by about 20% compared to the conventional method.

[Resource Allocation for LoRaWAN] (Adachi Lab.)

Low-power wide area networks (LPWANs), such as long-range wide area networks (LoRaWAN), are increasingly adopted as a communication standard for wireless sensor networks. In particular, LPWAN has been adopted for systems that periodically collect sensor data, such as environmental monitoring. However, continuous packet collisions may occur in periodic traffic systems due to adopting a simple random-access scheme in LPWAN. In addition, the use of low-cost nodes results in clock drift, rendering transmission cycle changes unintentionally.

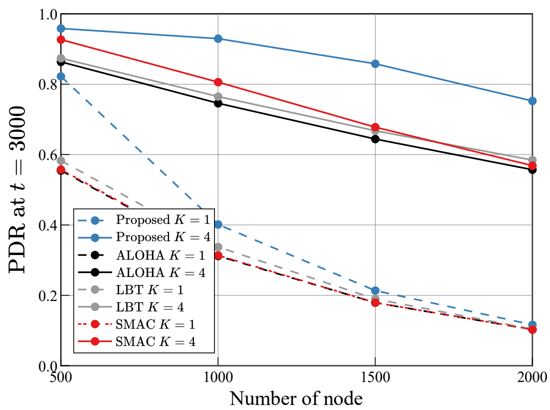


Fig. 2.4-13. PDR performance

Thus, this study proposes a centralized resource allocation scheme comprising clock drift compensation, frequency channel allocation, and transmission timing offset allocation to overcome these challenges. In the proposed scheme, GW compensates for the transmission cycle of the node based on the observed clock drift. Subsequently, the GW predicted future packet collision based on the periodic traffic feature and sequentially determined and allocated the transmission offset and frequency channel for each node. In particular, the proposed scheme can exploit a secondary effect of clock drift (continuous packet collision avoidance) by sequential allocation. Furthermore, based on probability, each node discarded a packet to avoid continuous packet collisions owing to clock drift compensation. The performance evaluation considering the LoRaWAN network has been conducted. Fig. 2.3-13 shows the computer simulation results of the PDR performance for each number of nodes. "LBT" denotes the CS-based autonomous decentralized packet collision avoidance method, and "SMAC" denotes the existing centralized control packet collision avoidance method for periodic traffic.

As shown in Fig. 2.4-13, the proposed scheme can improve the average packet delivery rate

(PDR) performance compared to the other method because it can allocate appropriate radio resources while utilizing clock drift.

2.4.4 Funds

[Grants-in-Aid for Scientific Research]

1. JST CREST "Practical applications of RFEH technology by combination of SSFET rectenna and piezoelectric transformer" in the area of Scientific Innovation for Energy Harvesting Technology, (Koichiro Ishibashi, Ryo. Ishikawa, and Koji Ishibashi)

2. Grant-in-Aid for Scientific Research (C), "Microwave rectifiers for flexible wireless power transfer system in emergency" (R. Ishikawa)

【Commissioned Research】

1. MIC SCOPE "Flexible LPWA Based on Environmental Dynamics"
   Koichi Adachi, Takeo Fujii

3．令和４年度　外部発表リスト

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シンポジウム講演

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その他の講演

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【6】 石橋孝一郎「エネルギーハーベスティング Beat Sensor とその応用展開」、ＵＥＣアライアンスセンターＩＣＴワークショップ、2023 年 2 月 14 日、電気通信大学

受賞

【1】 芦沢直、2022 年度 電子情報通信学会 マイクロ波研究会 学生研究優秀発表賞

【2】 OWPT 2022 Paper Award (N. Shindo, T. Kobatake, M. Matsuura, D. Masson, and S. Fafard, “Flight demonstration of power-over-fiber drone for aerial base stations,” The 4th Optical Wireless and Fiber Power Transmission Conference (OWPT 2022), OWPTp-01, Yokohama, 2022.)

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【4】 2022 年度 PN 若手研究賞（神藤夏季, 小畠大輝, 松浦基晴, “空中基地局に向けた光ファイバ給電ドローンの飛翔実験,” 電子情報通信学会フォトニックネットワーク研究会, PN2021-77, 2022 年.）

【5】 向田敦紀，2022 年電子情報通信学会スマート無線研究会研究奨励賞，2023 年 1 月（藤井研・前期博士課程学生）

【6】 須藤克哉，2022 年電子情報通信学会スマート無線研究会研究奨励賞，2023 年 1 月

【7】 藤井威生，第 33 回電波功績賞 総務大臣表彰 電波産業会，2022 年 6 月

【8】 藤井威生，電波の日関東総合通信局長表彰 総務省関東総合通信局，2022 年 6 月

【9】 平山尚貴，2022 年度 IEICE RCS 研究会「RCS 研究会初年度発表者コンペティション」優秀賞受賞，2023 年 1 月（安達研・前期博士課程学生）

【10】 安藤研吾，2021 年度電子情報通信学会無線通信システム（RCS）研究会活動奨

励賞，2022 年 6 月（石橋（功）研・前期博士課程学生）

【11】 中條宏郁，IEEE VTS Tokyo/Japan Chapter 2022 Young Researcher's Encouragement Award, 2022 年 9 月（藤井研・博士後期課程学生）

【12】 磯野直樹，2022 年度 IEICE RCS 研究会「初めての研究会」優秀発表賞，2022 年 6 月（石橋（功）研学生・博士前期課程学生）

【13】 Best Student Paper Award on ATC 2022

【14】 内村颯太，令和４年度目黒会賞，2023 年 3 月（石橋（功）研・博士前期課程学生）

【15】 奥井滉史，令和４年度目黒会賞，2023 年 3 月（石橋（功）研・学部生）

【16】 三輪健太，令和４年度目黒会賞，2023 年 3 月（石橋（功）研・学部生）

【17】 内村颯太，令和４年度修士論文優秀発表賞，2023 年 3 月（石橋（功）研・博士前期課程学生）

【18】 鈴木康介，令和４年度修士論文優秀発表賞，2023 年 3 月（安達研・博士前期課程学生）

【19】 奥井滉史，令和４年度卒業論文優秀発表賞，2023 年 3 月（石橋（功）研・学部生）

【20】 國井瑠偉，令和４年度卒業論文優秀発表賞，2023 年 3 月（石橋（功）研・学部生）

【21】 照井貫太，令和４年度卒業論文優秀発表賞，2023 年 3 月（石橋（功）研・学部生）

【22】 三輪健太，令和４年度卒業論文優秀発表賞，2023 年 3 月（石橋（功）研・学部生）

【23】 更屋貴大，令和４年度卒業論文優秀発表賞，2023 年 3 月（安達研・学部生）

【24】 園田晟也，令和４年度卒業論文優秀発表賞，2023 年 3 月（安達研・学部生）

【25】 纐見康平，令和４年度学長表彰，2023 年 3 月（安達研・博士前期課程学生）

【26】 向田敦紀，令和４年度学長表彰，2023 年 3 月（藤井研・博士前期課程学生）

【27】 中條宏郁，令和４年度学長表彰，2023 年 3 月（藤井研・博士後期課程学生）

【28】 Taro Miyamoto, Shusuke Narieda, Takeo Fujii, Hiroshi Naruse, The 37th International Conference on Information Networking (ICOIN) Best Paper Award, 2023 年 1 月

【29】 Gao Ying，電子情報通信学会超知性ネットワーキングに関する分野横断型研究会 RISING2022 優秀ポスター発表賞，2022 年 11 月（藤井研・博士後期課程学生）

【30】 原郁紀，2022 年度電気通信普及財団テレコムシステム技術学生賞，2023 年 3 月（石橋（功）研・博士後期課程修了生）

特許

【1】 石橋孝一郎、小川勇貴、「照明システム」、特願 2022-111922、2022 年 7 月 12 日
【2】 内村颯汰、飯盛寛貴、アブレウ ジュゼッペ、石橋功至、「基地局、ビームフォーミング方法およびビームフォーミングプログラム」、特願 2022-112198、日本、2022 年 7 月 13 日
【3】 田久修、宮本隆司、藤原洋志、藤井威生、安達宏一、「データ伝送方式」、特願 2022-125777、2022 年 8 月 5 日
【4】 田久修、宮本隆司、藤原洋志、藤井威生、安達宏一、「データ伝送方法」、特願 2022-125783、2022 年 8 月 5 日
【5】 大塚啓人、斉藤昭、本城和彦、石川亮、,“ループアンテナの給電装置,” 日本国特許第 7161750 号, 2022 年 10 月 19 日.
【6】 石橋功至、谷津峻太、柴田悠宇、遠藤秀樹、土岐爽真、「通信システム，通信方法およびプログラム」、特願 2022-192845、日本、2022 年 12 月 1 日
【7】 S. Uchimura, K. Ishibashi, H. Iimori, P. Klaine and S. Malomsoky, No. PCT/SE2022/051210, Dec. 20, 2022.
【8】 松浦基晴、「ダブルクラッド光ファイバおよび光ファイバ給電・信号伝送システム」、特願 2023-008721、2023 年 1 月 24 日
【9】 安達宏一、熊田遼汰、受信装置、受信方法および受信プログラム、特願 2023-021566、2023 年 2 月 15 日
【10】 上田康平、石橋功至、「通信システム、基地局および通信方法」、特願 2023-052725、日本、2023 年 3 月 29 日

広報・報道発表

【1】 Beyond 5G・6G 実現のためのセルフリー大規模 MIMO 向け ダイナミック TDD 技術を開発 −従来の約２倍の周波数利用効率を実現−, 電通大ニュースリリース, 2022 年 5 月 9 日
【2】 石橋孝一郎教授（情報・ネットワーク工学専攻）が CEATEC 2022 へ出展【10 月 18 日～21 日開催】（電通大 HP に掲載、2022 年 10 月 19 日）