Advanced Wireless & Communication
Research Center

ACTIVITY REPORT 2020

The University of Electro-Communications

Message from the Director, Prof. Takeo Fujii

2020 was a difficult year for research due to the blow of Covid-19. Many international and domestic conferences were canceled and shifted to virtual conferences. The activities of Advanced Wireless Communication Research Center (AWCC) were slightly decreased caused by the state of emergency in Japan. Many national projects however were continued without a big change of research plan and the research activities become increased in the latter part of the year. All professors, staffs, and students of AWCC continue their activities by considering safe of their health and maximizing the research output in the limited research environment. I hope we can overcome Covid-19 and return to a peaceful life.

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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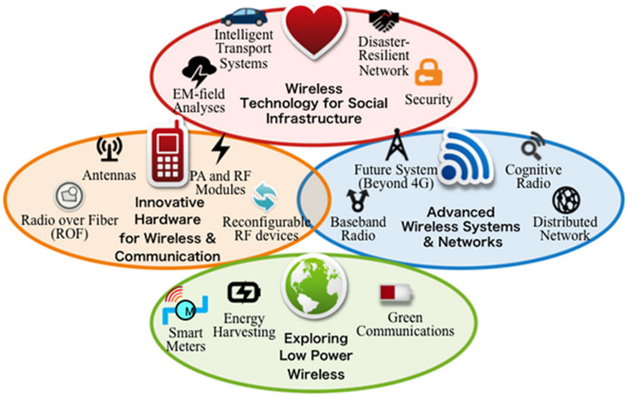
1. ABOUT AWCC

1.1 OVERVIEW

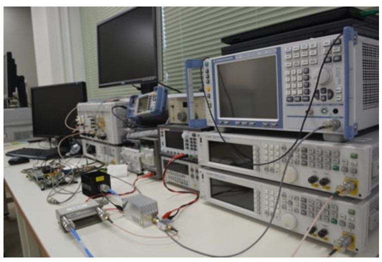


The Advanced Wireless Communication Research Center (AWCC) was launched in April 2005 with the aims of establishing a global hub for wireless communications; advancing education in wireless technology; industrial collaboration and technology transfer; and nurturing young engineers with strong emphasis 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

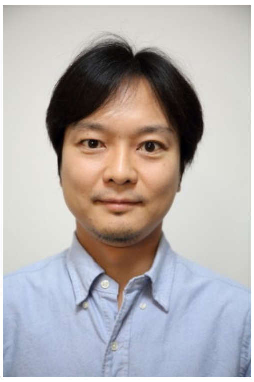
【Director, Full-time Prof. Takeo Fujii】

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 Associate Prof. Koji Ishibashi (Promoted to Professor in 2021)】

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 Communications Letters since 2016, IEEE Transactions on Vehicular Technology between 2016 – 2018, IEEE IEEE Transactions on Green Communications and Networking since 2016, and IEEE Open Journal of Vehicular Technology since 2019. He is a senior member of IEEE and a member IEICE. He was recognized as the Exemplary Reviewer from IEEE Wireless Communications Letters in 2012, 2013, 2014, and 2015. He was awarded excellent editor award from IEEE ComSoc MMTC in 2013. He is a coauthor of WPMC2020 Best Student Paper Award.

【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. Takayuki Inaba】

Takayuki Inaba received a B.S. degree from the Department of Physics, Tokyo Institute of Technology, in 1981, completed the M.E. program in physics in 1983. He received the Ph.D. degree in engineering from Tokyo Institute of Technology in 2001. Since April 2008, he has been with the University of Electro-Communications, where he is a Professor at the Department of Mechanical and Intelligent Systems Engineering, Graduate School of Informatics and Engineering. He has been engaged in research and development of radar signal processing, and adaptive array signal processing, and automotive radar systems. He is a senior member of IEEE. He is a recipient of the Telecommunications Advancement Foundation Award (32th), IEEJ Distinguished Paper Award (72th), 2014 IEEE AES Japan-chapter Best Paper Award, IEICE Communications Society Distinguished Contributions Award 2009, 2006 IEEE AES Japan-chapter Best Paper Award, and IEICE Communications Society Excellent Paper Award 2006. .

【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 Associate Prof. Ryo Ishikawa (Promoted to Professor in 2021)】

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.

【Visiting Professors】

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

【Cooperative Professors】

Prof. Yasushi Yamao, Ph.D.

Prof. Nobuo Nakajima, Ph.D.

Prof. Haruhisa Ichikawa, Ph.D.

Prof. Kazuo Ohta, Ph.D.

Prof. Sadao Obana, Ph.D.

Prof. Toshihiko Kato, 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. Hiroyuki Kasai, Ph.D.

Associate Prof. Toshiharu Kojima, Ph.D.

Associate Prof. Hisa-Aki Tanaka, Ph.D.

Associate Prof. Kazuki Nishi, Ph.D.

Associate Prof. Wu Celimuge, Ph.D.

Assistant Prof. Satoshi Ono, Ph.D.

Assitant Prof. Katsuya Suto, Ph.D.

【Cooperative Professors from Industry】

Prof. Kunio Uchiyama (AIST)

Prof. Yukihiko Okumura (NTT Docomo R&D)

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. Yukitsuna Furuya (WiTLa)

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. The goal is to develop such technologies.

2.1.2 Research Staffs and Their Specialties

Prof. Takayuki Inaba（Division Leader, ITS, Radar）
Prof. Takeo Fujii（ITS, Radio Environment Analysis (REA), DPRN, Wireless security）
Associate Prof. Koichi Adachi (Drone)

2.1.3 Major Research Outcomes in 2020

(A) Intelligent Transport System (ITS)

Advance technologies for Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I) communications towards automated driving are studied. Since Vehicular communications are conducted in fully distributed environments, wireless communication techniques for such environments are pursued. This work was supported by the Ministry of Internal Affairs and Communications (MIC) of Japan under the Strategic Innovation Promotion (SIP) program during physical years 2014 to 2016, MIC-1, "Development of V2V and V2I Communication Technologies necessary for Automated Driving Systems".

On the other hand, in order to realize fully automated driving, it is not enough by studying only vehicular communication issues, but necessary to discuss and collaborate with the researchers who study automated vehicle control and stand-alone sensors on the vehicles. Therefore, we established a project with related members to such subjects and collaborate on the Grants-in-Aid for Scientific Basic Research A, "Basic Research for Integrated Automated Driving System combining Stand-Alone Sensors and Cooperation by vehicle communications."

[V2V Packet Delivery Ratio Estimation based on Spectrum Database considering Packet Collision by using Positions and Density of Vehicles] (Fujii Lab.)

V2V communication is expected as one of the technologies to realize connected and automated driving. However, it is difficult to know the radio environment accurately in V2V communication and the method for avoiding packet collision and estimating radio environments is required. The measurement-based spectrum database (MSD) is one of the methods to estimate radio environments. The conventional method using the MSD can estimate radio environment with high accuracy by creating packet delivery ratio (PDR) maps. However, in that method, the accuracy of PDR maps is expected to be deteriorated significantly if the vehicle density changes between creating and using the maps. This paper proposes the method for correcting PDR maps considering packet collision by using positions and the density of vehicles. Furthermore, we analyze the proposed method by computer simulation.

We propose a method for estimating PDR considering packet collision by using positions and density of vehicles. This method corrects a PDR by multiplying the PDR not considering packet collision by the probability that packet collision does not occur. The PDR considering collisions of the packets from the transmitting vehicle to the receiving vehicle is found by

$$PDR'(\boldsymbol{C}_{\mathrm{Tx}}, \boldsymbol{C}_{\mathrm{Rx}}) = PDR_{\boldsymbol{C}_{\mathrm{Tx}}, \boldsymbol{C}_{\mathrm{Rx}}} \times PH(\boldsymbol{C}_{\mathrm{Tx}}, \boldsymbol{C}_{\mathrm{Rx}}) \ , \qquad (1)$$

where $\boldsymbol{C}_{\mathrm{Tx}}$ and $\boldsymbol{C}_{\mathrm{Rx}}$ are the meshes of the transmitting and the receiving vehicle, $PDR_{\boldsymbol{C}_{\mathrm{Tx}}, \boldsymbol{C}_{\mathrm{Rx}}}$ and $PH(\boldsymbol{C}_{\mathrm{Tx}}, \boldsymbol{C}_{\mathrm{Rx}})$ are the PDR not considering packet collision and the probability that the hidden collision does not occur when one vehicle transmits packets at $\boldsymbol{C}_{\mathrm{Tx}}$ and another vehicle receives at $\boldsymbol{C}_{\mathrm{Rx}}$.

In order to evaluate the performance of the proposed method, computer simulations using the C++ programming language are executed. Fig. 2.1-1 shows the layout of the simulation scenario. Each street of the crossroads has 5 m width and 215 m length. The simulation results show that the proposed method can estimate PDR more accurately than the method not considering packet collision. Fig. 2.1-2 shows the results of the simulation of the relationship between PDR and CDF for each number of vehicles. The results show that the accuracy of the proposed method decreases as the number of vehicles increases. The reason for the accuracy degradation is that the number of packets increased by rescheduling is not considered.

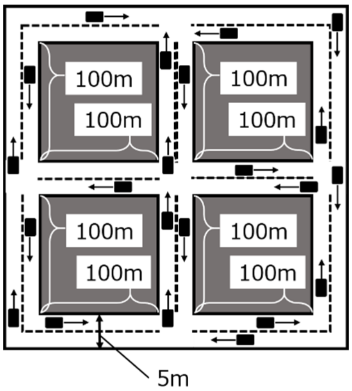


Fig. 2.1-1. The layout of simulation scenario

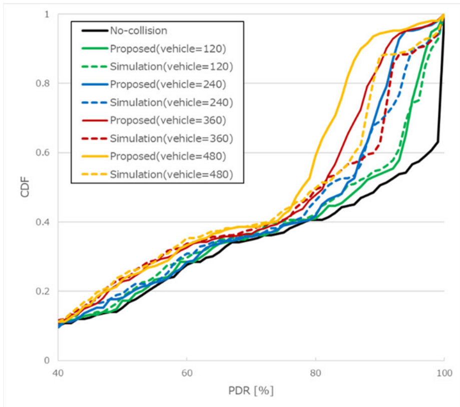


Fig. 2.1-2. The relationship between PDR and CDF for each number of vehicles

[Packet delivery rate information-based routing design for V2V networks with spectrum database] (Fujii Lab.)

To realize reliable vehicle-to-vehicle (V2V) communications, it is necessary to accurately estimate the radio propagation fluctuation owing to the mobility of vehicles. The measurement-based spectrum database (MSD) for distributed environments has attracted attention as an enabler to accurately estimate radio propagation. The MSD stores the average received signal power for each transmission and reception location. This information can be utilized to appropriately determine the modulation format and relay vehicle in V2V communications. However, from our previous work, it has been found that there is no correlation between the average signal power and the packet delivery rate (PDR) owing to the shadowing in the dense structures. Therefore, the communication reliability may be poor in this environment. This paper proposes a routing method based on the PDR in the MSD for multi-hop V2V communications. Furthermore, we analyze the proposed method by computer simulation.

In this study, the PDR information of each link is obtained from the MSD and used to select relay vehicles. When the estimated PDR of a link is X[%] or more, the link is extracted as a candidate for multi-hop V2V communications. Then, using the extracted links, the end-to-end communication route is constructed based on Dijkstra's method. We also propose the compensation method for the error using the confidence interval estimation. In general, shadowing and fading characteristics are heavily depending on geographical conditions, such as surrounding structures. Therefore, it is difficult to deterministically formulate the probability distribution of PDR for various environments. By considering the above fact, the confidence interval estimation based on Student's *t*-distribution is used to compensate for PDR errors.

To evaluate the performance of the proposed method, computer simulations using the C programming language are executed. Fig. 2.1-3 shows the layout of the simulation scenario. Each street of the crossroads has a 5 m width and 920 m length. When we use the compensation method, Fig. 2.1-4 shows the average number of hops, and Fig. 2.1-5 shows the average PDR. The simulation results show that we have confirmed that the average PDR can be accurately compensated using the confidence interval estimation even if the PDR includes the estimation error.

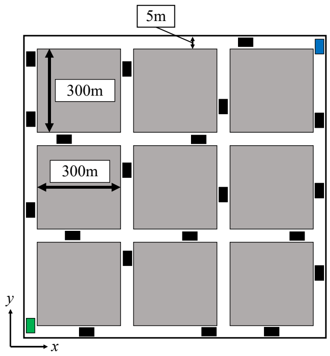


Fig. 2.1-3. The layout of the simulation scenario

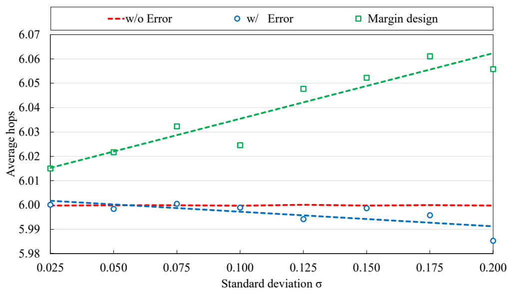


Fig. 2.1-4. The average number of hops based on the PDR compensation

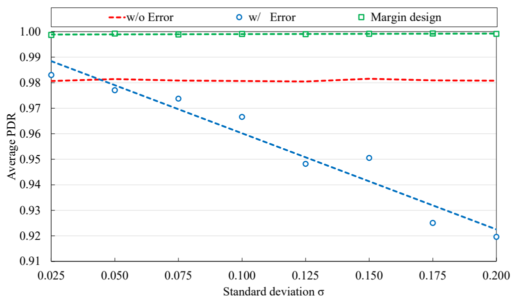


Fig. 2.1-5. The average PDR based on the PDR compensation

[ULA Equipped UAV-BS for Low Power Wireless Networks] (Adachi Lab.)

This research considers a scenario where an unmanned aerial vehicle (UAV) equipped with a uniform linear array (ULA) acts as a relay in a cellular system. Due to the line-of-sight (LoS) channel, the UAV can receive a signal with high power from the desired base station (BS). However, at the same time, the interference from neighboring BSs becomes significant. Thus, it is necessary to handle this interference so that the UAV can have a better signal-to-interference plus noise ratio (SINR). This research introduced coordinated multi-point (CoMP) transmission and applied minimum mean square error (MMSE) based beamforming to suppress the interference from neighboring BSs. By improving the SINR, the area where the UAV can be deployed expands. Thus, it can be more flexibly deployed to increase the system channel capacity. We have conducted numerical simulation. Fig. 2.1-6 shows the average SINR performance at a user equipment (UE). By deploying UAV, the received SINR increases. The channel capacity of each UE is shown in Fig. 2.1-7, which shows that the proposed approach can improve the channel capacity due to the flexible deployment of UAV and beamforming.

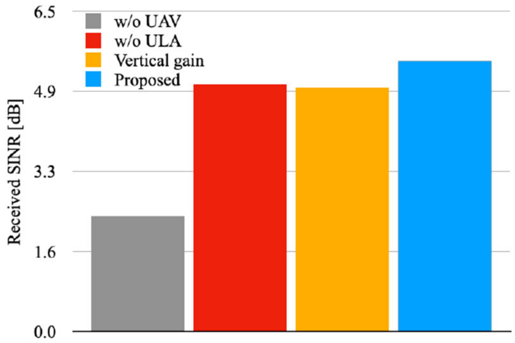


Fig. 2.1-6 Received SINR performance.

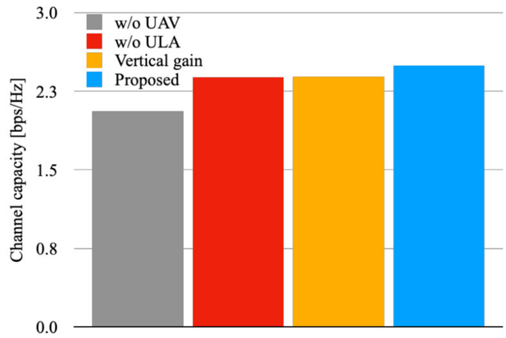


Fig. 2.1-7 Channel capacity.

(B) Radar Signal Processing

[Vehicle Onboard Radar] (Inaba Lab.)

We have proposed stepped multiple frequency (SMF) modulation. The unique radar modulation/demodulation method can achieve a high range resolution and a long-range detection performance by a narrow receiver bandwidth compared to transmitting bandwidth. That is why this method achieves not only a high range resolution but a long-range detection performance. Stepped multiple frequency CPC modulation that is the one of SMF made it possible to obtain the good range side-lobe in spite of using short code length. Authors have developed the millimeter wave radar using stepped multiple frequency CPC. These millimeter wave radars meet the specified low-power radio station standard of the millimeter wave in Japan. In recent years, Japanese radio wave laws for short range radar has been modified for use of the ultra-wide bandwidth of 5 GHz in 79 GHz band. The advantage of this method itself must be more remarkable for use of the ultra-wide bandwidth. In the case of ultra-wideband, we face the velocity and range ambiguity problems, since both the pulse repetition interval and the frequency steps should be sparse.

To overcome the problems, we proposed the sparse frequency division scheme, in which the frequency steps are designed for obtaining good side-lobe characteristics by fewer number of frequency steps without range ambiguity. The target range and velocity are obtained by the signal processing of iterative signal subtraction and frequency estimation (shown in Fig.2.1-7). Simulation results indicated that the RMSE of range of each target shows a good agreement with CRLB. These proposed methods can detect the targets having different receiving signal level of power among them with the resolution of ultra-wideband without ambiguity in both velocity and range profiles.

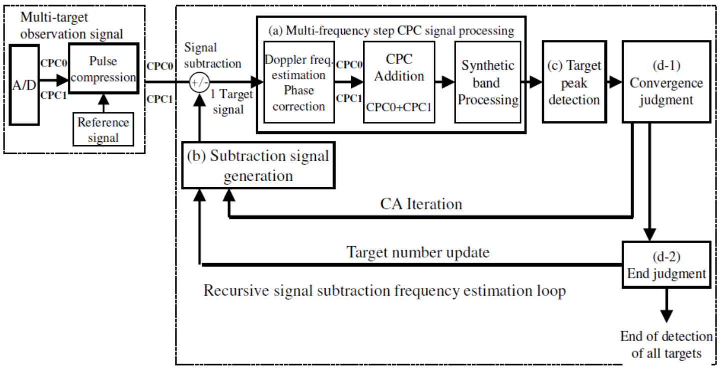


Fig.2.1-7 Block diagram of the signal processing of iterative signal subtraction and frequency estimation method in stepped multiple frequency radar.

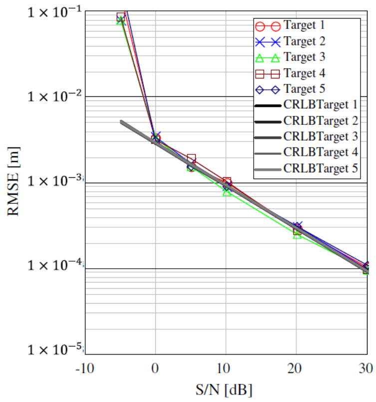


Fig. 2.1-8 Target range estimation RMSE and CRLB of the proposed method.

2.1.4 Funds

【Grants-in-Aid for Scientific Research】

1. Fund for the Promotion of Joint International Research (Fostering Joint International Research) "Research on Advanced Wireless Vehicle Networks with Learning Spectrum Environment for Cooperative Self Driving"
   T. Fujii
2. Scientific Research C "Research on Energy Efficient Wireless Communications Network Using UAV-BS"
   K. Adachi

【Commissioned Research】

1. Strategic Information and Communications R&D Promotion Program (SCOPE), "R & D of Ultra-wide band coherent radar technology"
   T. Inaba, Y. Yamao and M. Akita

【Cooperative Research】

1. "Research on communications technology for machine tools"
   K. Adachi and Y. Yamao

【Other Funds】

1. "Parameter design for stepped multiple frequency CPC radar", Academic consulting T. Inaba
2. "Analysis program of stepped multiple frequency CPC", License agreement T. Inaba

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. K.Wada	Microwave Filters and Their Applications
Associate Prof. R. Ishikawa	Microwave/Millimeterwave Devices and Circuits
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 2020

(A) [High-efficiency GaN HEMT outphasing power 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 an outphasing power amplifier with a compact combiner. The combiner could be successfully shrunk by applying a series-load-compensation connection scheme. In addition, a dual-power-level design was applied for the power amplifier to increase the dynamic range of its high-efficiency power. A fabricated GaN HEMT outphasing power amplifier exhibited a peak drain efficiency of 77% with a saturation power of 37dBm at 3.92 GHz. In addition, a drain efficiency of more than 50% was maintained within an output back-off of 7 dB. (Fig. 2.2.1)

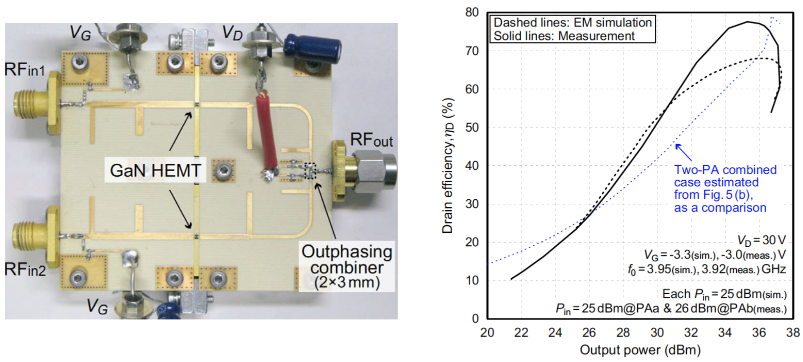


Fig. 2.2.1 Fabricated GaN HEMT outphasing power amplifier with a compact combiner, and its characteristics

(B) A 12-GHz-band loop antenna array with reflector integrated on a Teflon multi-layer substrate for 4-channel multiplexing OAM communication (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). Based on this principle, we have successfully developed a 4-channel multiplexing OAM communication by using a loop antenna array with reflector integrated on a Teflon multi-layer substrate at 12-GHz band. The loop antenna array was placed on a Teflon substrate, and the terminal was pulled out to the back of the reflector with vias. The measured isolation of transmission for OAM communication at 12.4 GHz is more than 20.9 dB for a distance of 4 mm. (Fig. 2.2.2)

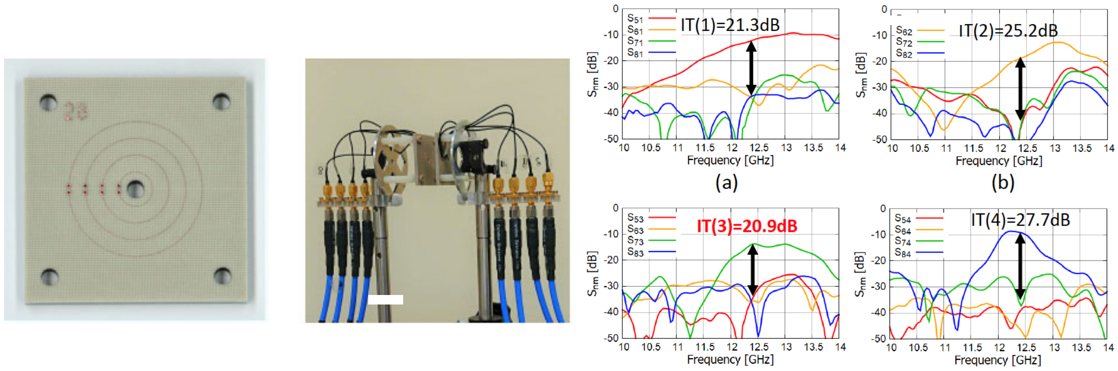


Fig. 2.2.2 Constructed 12-GHz-band 4-channel multiplexing OAM communication system, and its characteristics

(C) A 12-GHz-band loop antenna array with reflector integrated on a Teflon multi-layer substrate for 4-channel multiplexing OAM communication (Ishikawa Lab.)

A circular loop antenna array system has been successfully developed for a short-range large-capacity communication and power charging, where both orbital angular momentum (OAM) four-eigen-value multiplexing communication at 5-GHz band and wireless power transfer (WPT) at megahertz band are simultaneously realized. To improve a WPT efficiency, a spiral reflector was applied instead of a normal reflector plane. In a fabricated this system, the WPT efficiency of 82.6% was achieved at 41 MHz, while keeping a four-value multiplexing OAM communication at 5.23 GHz. (Fig. 2.2.3)

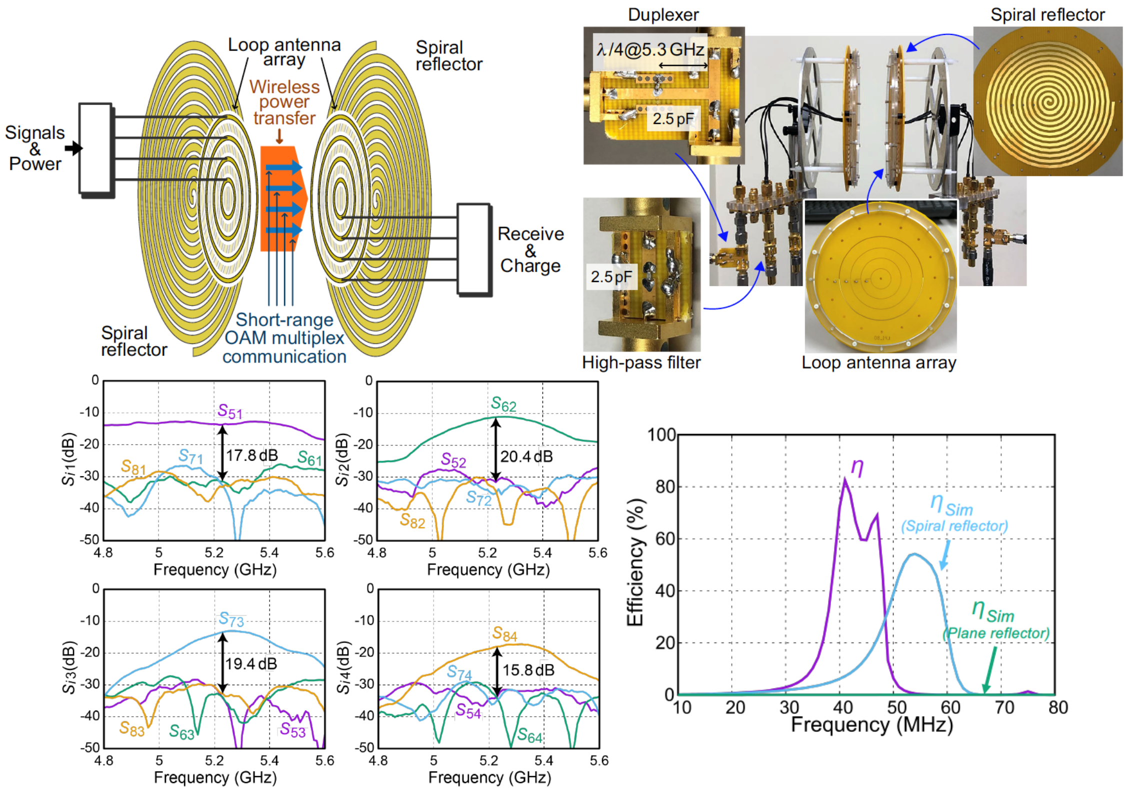


Fig. 2.2.3 Proposed circular loop antenna array system with spiral reflector for simultaneously realizing short-range OAM multiplex communication and WPT, constructed its system, and its characteristics (left: OAM, right: WPT)

(D) Photonic Digital-to-Analog Conversions (DACs) for RoF Systems (Matsuura Lab.)

Digital-to-analog conversion (DAC) is an essential function that converts a digital signal to an analog signal. DACs are used in various fields such as communication networks, voice processing, and modern radars. However, these DACs have complicated schemes, and need additional electrical signal processing to perform the DACs.

Semiconductor optical amplifiers (SOAs) have many advantages in terms of optical signal processing (OSP) applications such as small footprint, low switching energy, high nonlinearity, and ability of monolithic integration. In particular, quantum-dot SOAs (QD-SOAs) provides advantages on high speed operation and broadband gain. By utilizing the property, we have proposed a photonic DAC using blue chirp in a QD-SOA. However, the resolution improvement by optimizing various parameters is needed for practical use. In this year, we paper presents a 4-bit resolution of photonic DAC based on all-optical binary-to-hexadecimal conversion using a blue chirp in a QD-SOA and the following blue-shift filtering. We demonstrate a 10-Gbps DAC and assess the resolution performance.

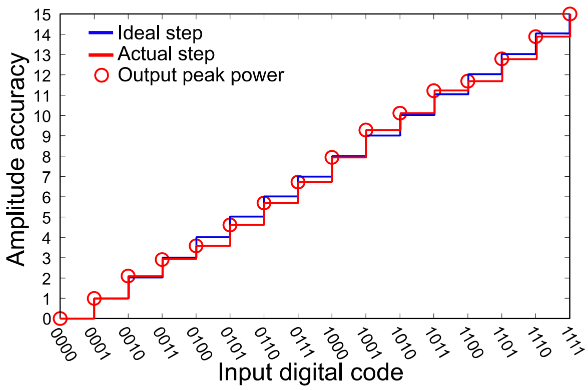


Fig.2.2.4 Ideal (blue line) and actual (red line) step functions for 4-bit DAC. Red open circles show measured amplitude of output 16-level amplitude signal.

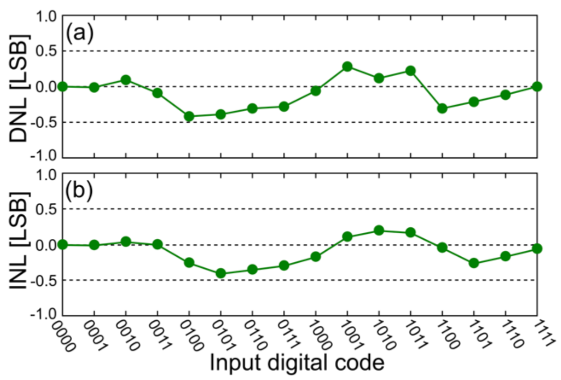


Fig.2.2.5 (a) Differential non-linearity (DNL) and (b) integral non-linearity (INL) of DAC for various input digital codes.

To evaluate the conversion performance of the DAC, we measured the amplitude accuracy of the output 16-level amplitude signal converted by the DAC. Fig. 2.2.4 shows the ideal (blue line) and actual (red line) step functions for the presented 4-bit DAC. The output pulse amplitude is normalized by 16 steps, and the one step corresponds to the smallest increment step of the DAC output between two adjacent levels. Here, the ideal DAC step is defined as one least significant bit (LSB). Fig. 2.2.5 shows the differential non-linearity (DNL) and the integral non-linearity (INL) of the presented DAC. The DNL is defined as the deviation of the actual step from the ideal step, whereas the INL is defined as the deviation of the DAC output from the ideal transfer function adjusted for the best-fit. The maximum absolute values of the DNL and the INL were 0.417 LSB and 0.400 LSB, respectively. All the DNL and INL values were within ±0.5 LSB, which can provide no missing codes for the 4-bit photonic DAC.

2.2.4 Funds

【Grants-in-Aid for Scientific Research】

1. Grant-in-Aid for Scientific Research (C),"Microwave OAM Antenna" (A. Saitou)

【Commissioned Research】

1. MIC, SCOPE, "Research and development of personal area high-speed and large-capacity wireless communication and wireless power transmission module" (R. Ishikawa, K. Honjo, Y. Takayama, A. Saitou, H. Suzuki)

【Cooperative Research】

1. RF device technologies Inc. "Study on novel devices and its evaluation methods for wireless communications" (R. Ishikawa)
2. SoftBank Group Corp. "Low power consumption amplifier" (R. Ishikawa)
3. 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)

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

2.3.3 Major Research Results in 2020

[Low Storage Radio Map Using Statistical Inference] (Fujii Lab.)
A crowdsourcing-assisted radio map has attracted attention for providing statistical information about primary users to secondary users. An overview of the crowdsourcing-assisted radio map is shown in Fig. 2.3-1. In crowdsourcing, distributed mobile terminals observe the radio environment in each location and report the observed samples to the cloud. The radio map is constructed by averaging the received signal power samples in each mesh. However, if the outdated instantaneous received signal power samples are not deleted, the registered data size in the cloud may become large. Thus, we propose two methods for determining the required sample size to estimate the average received signal power. In the first method, the interval estimation and central limit theorem are utilized to estimate the required sample size in each mesh. As another method, the t-test in hypothesis testing is used. Then, the cloud calculates the average received signal power based on the estimated sample size. Fig. 2.3-2 shows the average root mean squared error (RMSE). Here, $1-\alpha$ is the confidence coefficient. In this figure, "w/o deletion" calculates the average power in each mesh without deletion of samples. "Constant 100" constructs the radio map using 100 samples in each mesh. Additionally, the forgetting factor-based method randomly extracts the samples for 10% from measured datasets. Meanwhile, Fig. 2.3-3 shows the cumulative distribution function of the registered data size per mesh. From these results, it can be confirmed that the proposed methods can accurately estimate the radio environment while notably reducing the registered data size.

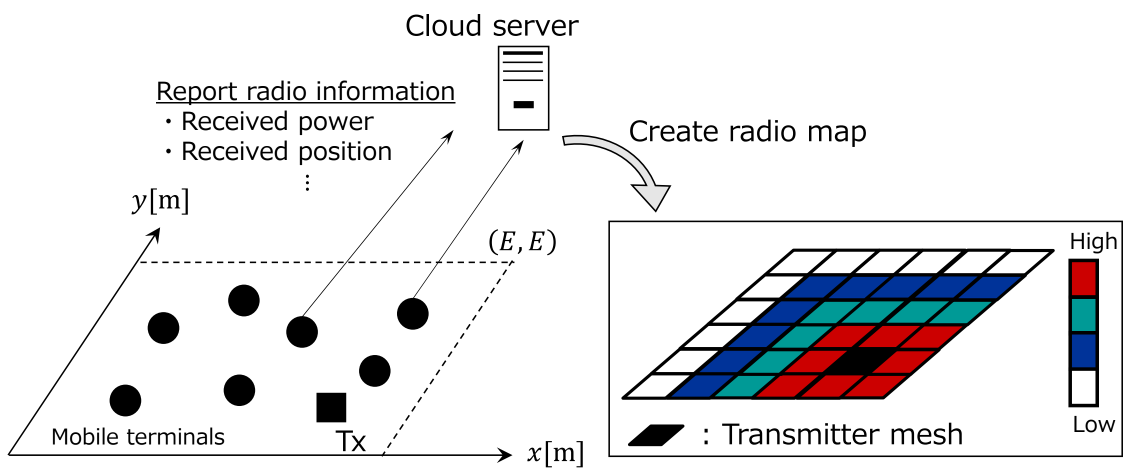


Fig. 2.3-1 Overview of radio map.

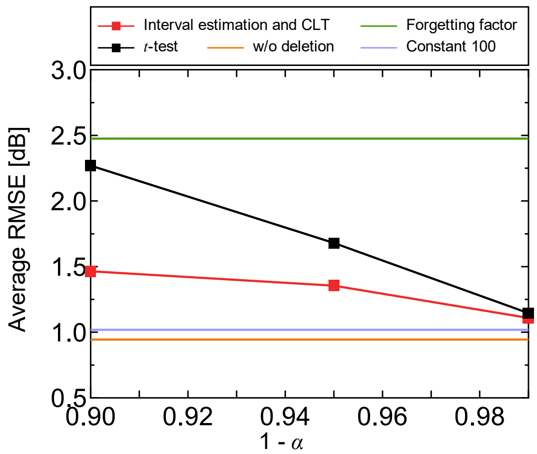


Fig. 2.3-2 Average RMSE.

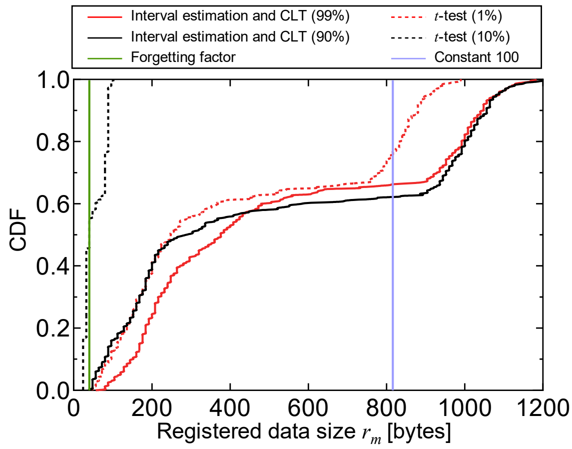


Fig. 2.3-3 Registered data size per mesh.

[Sequential Control of Allocated Bandwidth According to Required Throughput] (Fujii Lab.)

Accurate knowledge of spectrum opportunities is a key factor for dynamic spectrum sharing. As an approach to managing spectrum resources to know the spectrum opportunity, an approach to estimate the spatial white space and aggregate interference by constructing the measurement-based spectrum database has been considered. As one of the spectrum sharing methods based on the spectrum database, an algorithm that combines power control and spectrum band division allocation has been proposed to maximize downlink throughput. The problem with that research is that it focuses on maximizing throughput, so it gives extra spectrum resources than the required value of throughput, which leads to a decrease in spectral efficiency. Therefore, the previous research cannot deal with the scenario of spectrum sharing among many different systems and base stations. To solve this problem, we proposed a method to control the spectrum bandwidth sequentially according to the required throughput by centrally managing the required throughput of each operator in the spectrum database. An overview of the database-managed bandwidth control according to the required throughput is shown in Figure 2.3-4. In this initial research, the bandwidth of all operators is increased sequentially until the required throughput was satisfied by all operators, without considering mutual interference and power control. Figure 2.3-5 shows the spectral efficiency and Figure 2.3-6 shows the areal spectral efficiency. These figures show that the proposed algorithm can increase the spectral efficiency compared to previous researches. In the future, we will consider the mutual interference and the smart bandwidth control method.

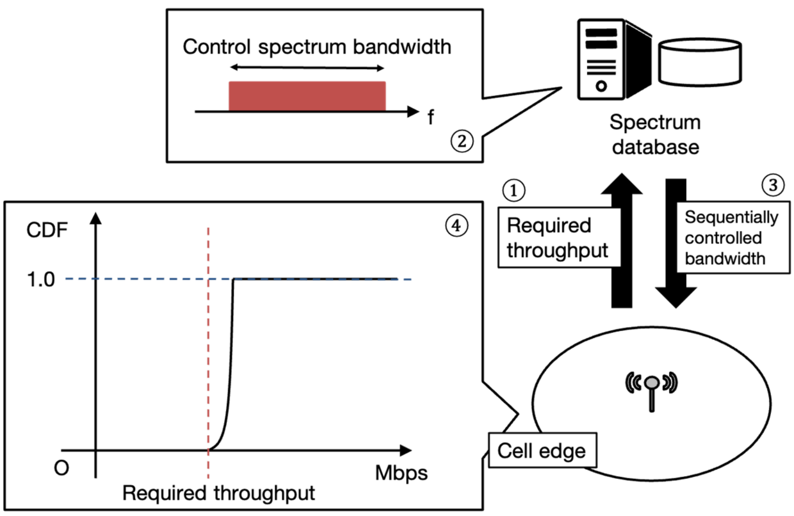


Fig. 2.3-4 Overview of database-managed bandwidth control according to required throughput.

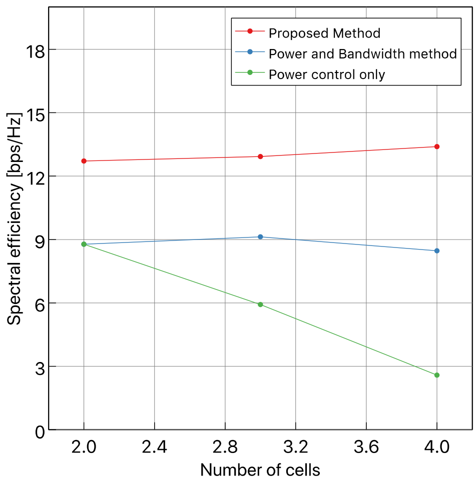


Fig. 2.3-5 Spectral efficiency.

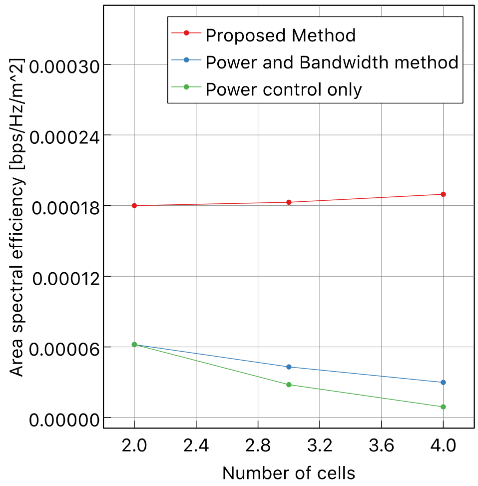


Fig. 2.3-6 Area spectral efficiency.

[Highly Accurate Prediction of Radio Propagation based on Compensation of Clutter Loss for Spectrum Sharing] (Fujii Lab.)

ITU-R P.2108 clutter loss model has been proposed to estimate the propagation loss considering the dominant buildings around Tx and Rx. In recent years, this model has been considering as the simple method to calculate interference for spectrum sharing. However, in this model, the propagation loss may be overestimated compared to the actual loss if the clutter height is too high. In this case, interference between different systems occur. Additionally, this model implicitly assumes that the altitudes are equivalent between the transmitter and the receiver. Therefore, the estimation accuracy of this model varies depending on the altitude difference between the transmitter and the receiver. In this research, we propose an improved clutter loss model by considering the dominant path and the altitude difference. In the proposed method, as shown in Fig. 2.3-7, the building with the largest elevation angle from the transmitter and receiver is considered as the dominant building, and the clutter loss is calculated on each transmitter and receiver. Then only the smaller one is considered as the clutter loss. In addition, the height difference between the antenna and the clutter is cut off when the height difference is 50 [m] or more for considering dominant path. Fig 2.3-8 and Fig 2.3-9 show the cumulative probability distribution (CDF) of the estimated received power error in the urban and suburban environments, respectively. From these results, it can be seen that the proposed method can reduce the probability of interference between different systems to 1% or less compared to other methods.

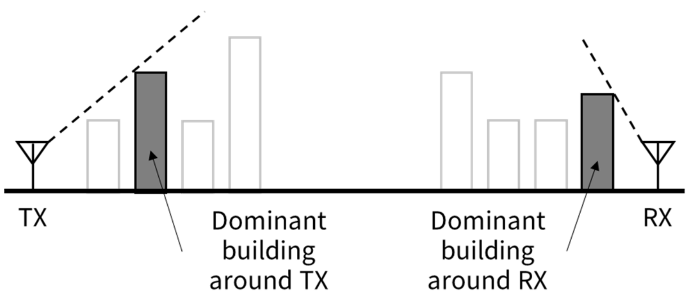


Fig. 2.3-7 dominant buildings around Tx and Rx

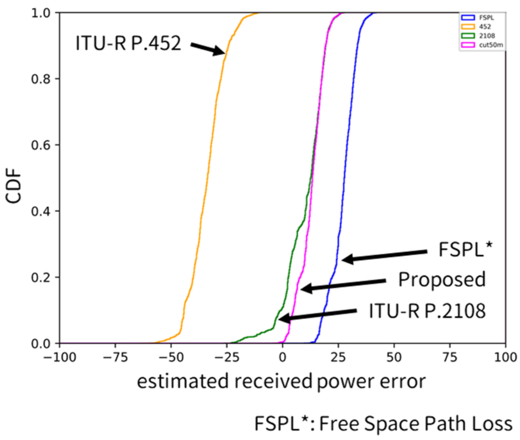


Fig. 2.3-8 CDF of the estimated received power error in the urban environment

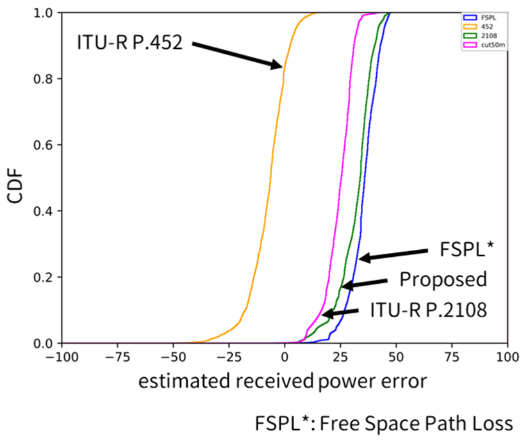


Fig. 2.3-9 CDF of the estimated received power error in the suburban environment.

[Radio and Computing Resource Allocation for Mobile Edge Computing] (Adachi Lab)

In this research, we focus on balancing the energy consumption, the processing delay and the communication quality for multi-user wireless powered-mobile edge computing (WP-MEC) systems. MEC can compute alternatively heavy tasks of wireless devices (WDs) and wireless power transfer (WPT) can charge the batteries of WDs wirelessly. WP-MEC realizes power-saving in IoT sensor networks. In this system, centralized control at the AP can reduce packet collisions, but it incurs the overheads because of exchanging control information. Thus, this research proposes a decentralized probabilistic binary offloading (PBO) strategy. By PBO strategy, each WD probabilistically selects one of two modes, i.e., offloading and local computing, instead of centralized control by an AP as shown in Fig. 2.3-10. Fig. 2.3-11 shows the comparison of PDR with PBO strategy and with offloading probability $p_k = 1$, i.e., offloading all tasks. The figure shows that the proposed PBO can improve the packet delivery rate (PDR) perforamnce compared to all offloading strategy.

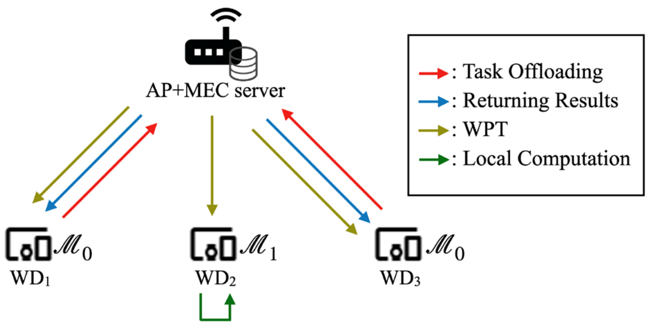


Fig. 2.3-10 A schematic diagram of WP-MEC with binary offloading.

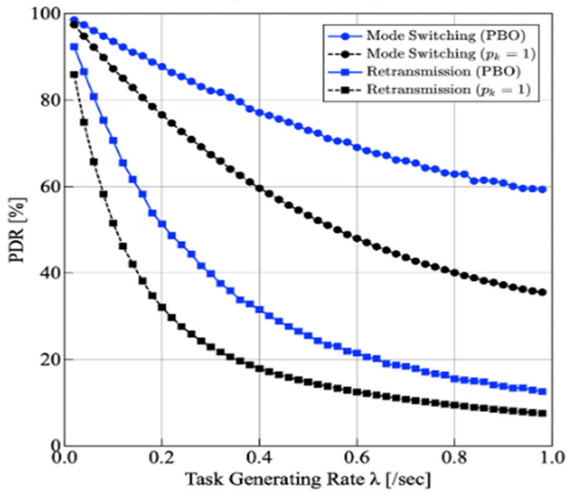


Fig. 2.3-11 Comparison of PDR performance.

[Q-Learning Based Resource Allocation in LPWA] (Adachi Lab.)

In recent years, with the breakthrough development of Internet-of-things (IoT) and machine-to-machine (M2M) communication, wireless sensor networks are expected to become more important. Low power wide area (LPWA) networks such as long-range wide area network (LoRaWAN) have attracted attention as a network standard for wireless sensor networks. LoRaWAN generally adopts a pure ALOHA protocol as the MAC layer access protocol. However, if multiple wireless devices transmit packets on the same frequency channel simultaneously, a packet collision happens at a fusion center (FC) that collects wireless devices' information. In particular, packet collision becomes a serious problem in event-triggered traffic generated by event detection as shown in Fig. 2.3-12. To tackle the packet collision problem, we have proposed an autonomous decentralized traffic control by machine learning. This research installs a reinforcement learning agent and the event packet transmission probability in each device. The proposed scheme consists of two steps. Firstly, the transmission timing offset of each device is autonomously set by reinforcement learning. Then, the event packet transmission probability is determined based on the success rate of event packet transmission. The performance evaluation considering the LoRaWAN network has been conducted. Fig. 2.3-13 shows that the proposed scheme can improve the average packet delivery rate (PDR) performance compared to the conventional ALOHA protocol.

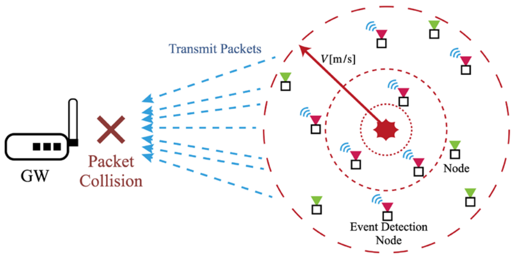


Fig. 2.3-12 Packet collision due to event-triggered traffic

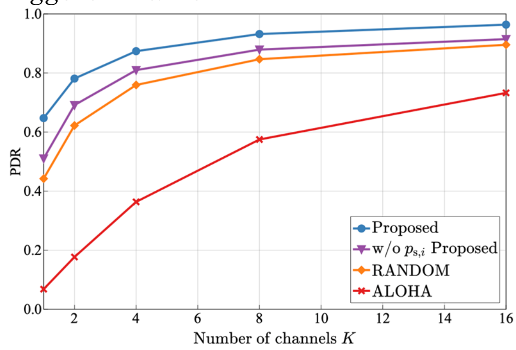


Fig. 2.3-13 Average PDR performance of the proposed traffic control scheme.

[Packet-Level Index Modulation for LPWAN] (Adachi lab)

The long range wide area network (LoRaWAN) is one of the enabling technologies for low power wide area

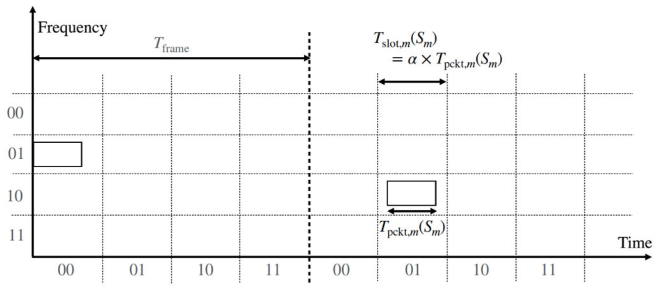


Fig. 2.3-14 Example of packet transmission in PLIM.

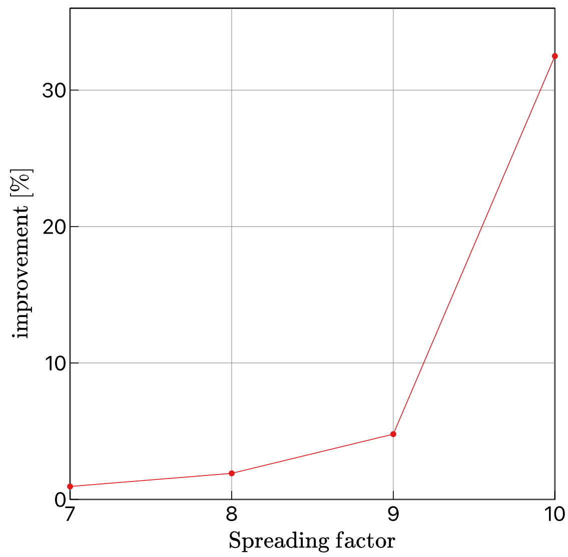


Fig. 2.3-15 Improvement of number of bits conveyed by one packet over conventional

(LPWA) networks. Since the packet transmission drains the LoRaWAN nodes' battery, the packet collision results in a waste of limited power. In addition, the quantity of data that each node can transmit is limited by the duty cycle (DC). Thus, it is necessary to develop a simple but effective transmission strategy that efficiently utilizes limited battery at each LoRaWAN node. This study proposes packet-level index modulation (PLIM) that conveys additional information bits by selecting a combination of time slot and frequency channel, i.e., index, as shown in Fig. 2.3-14 The proposed PLIM can compensate for the data rate limitation above by taking advantage of the sparse transmission in time. Fig. 2.3-15 shows that the proposed PLIM can increase the information bits conveyed by one data packet. The PLIM is more effective as the spreading factor (SF) is higher.

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

Future wireless communication such as Beyond 5G and 6G would accommodate massive number of devices, as represented by Internet-of-Things (IoT). In order to realize efficient low-latency data transmission of large number of devices, designing multiple access schemes is crucial. As one of the promising techniques, grant-free non-orthogonal multiple access (GF-NOMA) in which the base station (BS) does not exclusively assign radio resources to active users for data transmission has been actively investigated. This fiscal year, we have proposed two GF-NOMA schemes: 1) one with frequency spreading and 2) one with time-and-frequency spreading, as shown in Fig. 2.3-16. In the former scheme, a multi-antenna BS estimates the active users and channels from the overlapped pilot signals spread over the frequency domain via a hyperparameter-free coordinate descent (CD) algorithm without a priori information of the channels. Fig. 2.3-17 shows the normalized mean squared error (NMSE) performance of GF-NOMA with our proposed algorithms and demonstrates that our proposals outperform the conventional scheme, namely NNLS, and can be comparable to the ideal maximum likelihood (ML) scheme with the perfect knowledge of the noise variance. On the other hand, the latter scheme makes full use of both the time and frequency domains and employs a spreading pattern that differs between the pilot and transmitted data. Moreover, the BS estimates the active users and channels via generalized multiple measurement vector approximate message passing (GMMV-AMP) and the transmitted

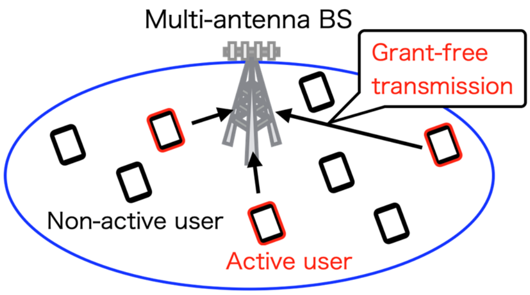


Fig. 2.3-16 GF-NOMA system

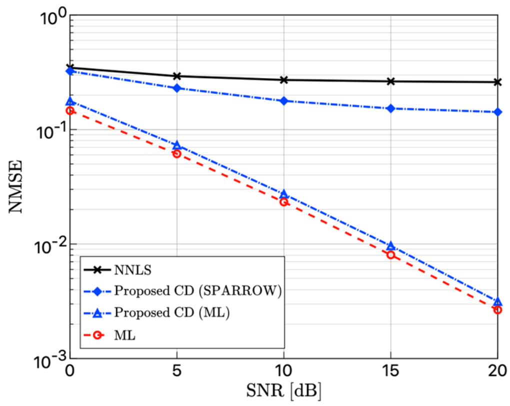


Fig. 2.3-17 NMSE performance of the proposed GF-NOMA scheme.

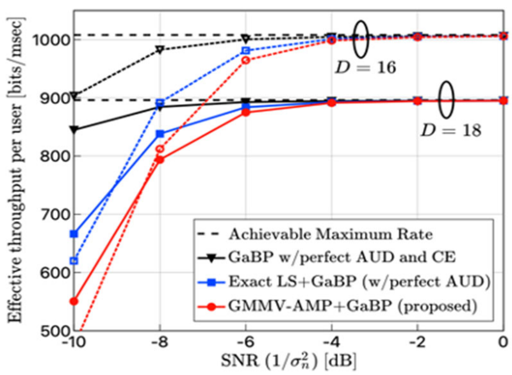


Fig. 2.3-18 Effective throughput per user of the proposed GF-NOMA.

data via Gaussian belief propagation (GaBP). Fig. 2.3-18 shows the effective throughput per user of the proposed scheme where 50 of 500 users are active. As seen from the figure, the proposed scheme can achieve the higher effective throughput than 100[bytes/msec] even though it estimates both the active users and channels. These results have been already published in and submitted to IEEE journals, respectively.

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

Massive MIMO (mMIMO) systems will provide enormous degree of freedom, which enables the next-generation of wireless systems such as Beyond 5G and 6G. Recently, cell-free mMIMO (CF-mMIMO) systems consisted of collaborative spatially distributed access points are discussed in order to make full use of capability of mMIMO systems and address the limitation due to spatial correlations, as shown in Fig. 2-3-19.

However, the flexible beamforming (BF) design for CF-mMIMO has not been studied to serve multiple user equipment (UEs) with a different number of antennas or with a different up/down transmission requirements. To this end, we proposed 1) BF design for serving user-heterogeneous UEs using multi-linear generalized singular value decomposition (ML-GSVD) and 2) BF design for dynamic TDD architecture using Lagragian dual transform (LDT) and quadratic transform (QT). Figure 2.3-20 shows the achievable sum-spectral efficiency (SE) of our proposed ML-GSVD based BFs and conventional BF (MMSE and MRC) in downlink scenarios. Figure 2.3-21 shows the achievable sum-SE of our proposed BF and conventional BF (MMSE). Both proposed BF schemes outperform conventional BF in terms of SE. These results have been already reported in domestic conferences.

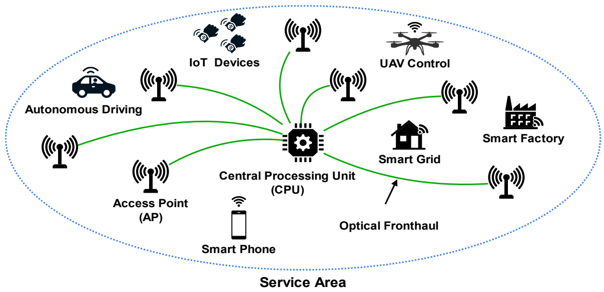


Fig. 2.3-19 Concept of CF-mMIMO

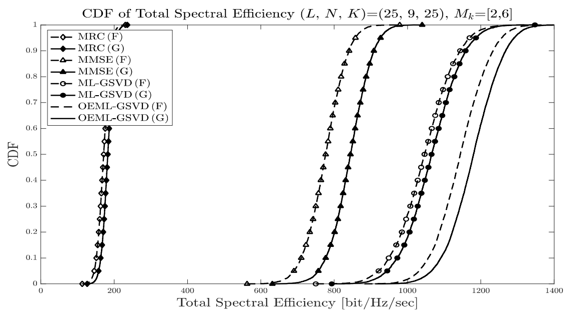


Fig. 2.3-20 CDF of the total SE for the proposed and conventional BFs in downlink.

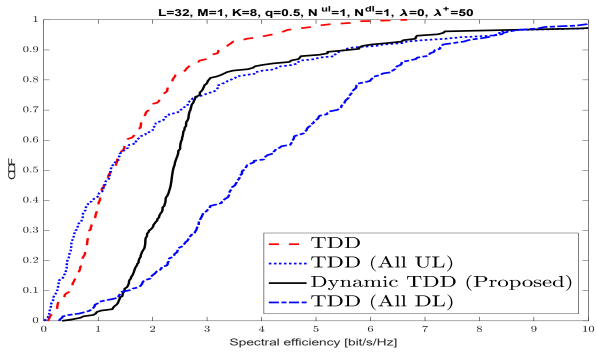


Fig. 2.3-21 CDF of the sum SE for the proposed and conventional BFs in dynamic TDD.

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

Millimeter-wave communications are expected to be foundations of Beyond 5G and 6G wireless architectures. Recently, several robust beamforming design methods taking into account random channel blockages have been proposed, as shown in Fig 2.3-22. Although these methods show robustness against such blockages, the computational complexity increases exponentially with number of base stations and users. This is due to the exponential growth of possible combinations of blockage patterns. To this end, we have proposed the low-complexity robust beamforming design based on weighted sum rate maximization together with an effective weight design for the proposed method. From the small number of constraints in the optimization problem, it is clear that the proposed method reduces the computational complexity by up to 1/100. Figure 2.3-23 shows effective throughput of our proposed method where blockage probabilities between each base stations and users are randomly chosen from 20% to 60%. As seen in the Figure 2.3-23, our proposed method can achieve the comparable performance to the conventional method while significantly reducing the computational complexity. This result has been already reported in the international conference.

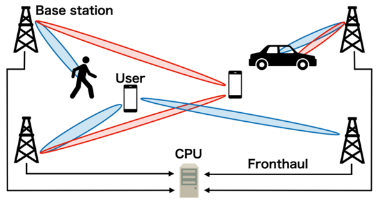


Fig. 2.3-22 System model of CoMP millimeter-wave communications with random blockages

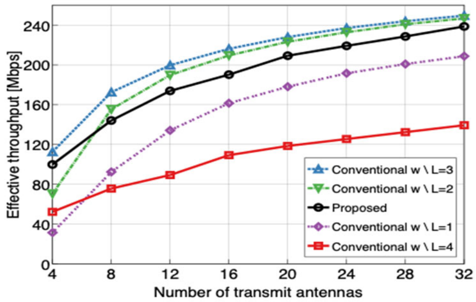


Fig. 2.3-23 Effective Throughput of the proposed and conventional method

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

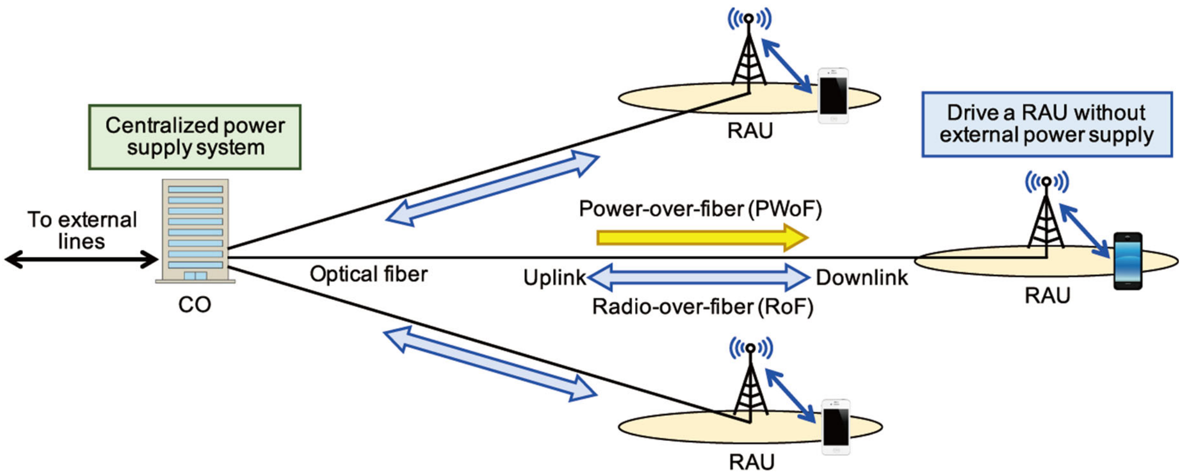


Fig. 2.3.24 Schematic view of optically powered RoF networks.

Radio-over-fiber (RoF) is an attractive approach for transmitting radio-frequency (RF) signals over an optical fiber laid between a central office (CO) and a remote antenna unit (RAU), and has the advantages of low loss, wideband, and no electromagnetic interference. Since the main elements can be centralized in the CO, the configuration of the RAU can be simplified. However, RoF systems require an external power supply to RAUs, so there is a problem that the installation place of RAUs is limited and RAUs do not operate when a power failure occurs. Therefore, power-over-fiber (PWoF) systems that transmit signals and power supplied to RAUs from a CO over the same optical fiber has attracted much attention as shown in Fig. 2.3.24.

Recently, we have demonstrated the PWoF experiment for RoF applications using a conventional multimode fiber (MMF). Then, the signal degradation due to the crosstalk between data signal and feed light was observed, and the degradation depended on the feed light power and the MMF link length. We also observed the spectrum analysis of the feed light in a MMF link. For these reasons, we think that it is very important to evaluate quantitatively the noise due to the crosstalk between data signal and high-power feed light in MMFs. In this year, we evaluate the relative intensity noise (RIN) for PWoF using MMFs. The results show that the RIN of feed light strongly depends on the feed light power and the MMF link length.

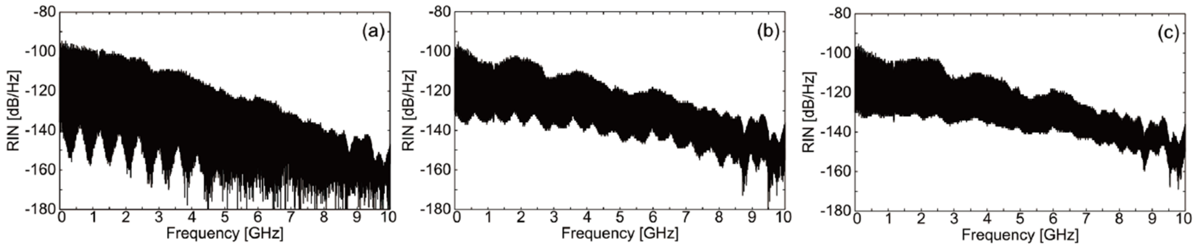


Fig. 2.3.25 RIN spectrum of feed light after (a) 0 km, (b) 2 km, and (c) 4 km MMF transmission when output power of FRL was set to 10 W.

Figure 2.3.25 shows the RIN spectrum of the feed light after 0 km, 2 km, and 4 km MMF transmission, when the output power of a feed light source generated by a Fiber Raman laser (FRL) was set to 10 W, respectively. It was found that the noise level was increased as the transmission distance was increased. In other words, the noise level was increased during the feed light transmission. On the other hand, even when the transmission length was increased, the maximum value of RIN was hardly increased. From these results, the noise characteristics induced by the feed light source strongly depends on the feed light power and the transmission length, and is closely related to the nonlinear effects in MMFs.

2.3.4 Funds

【Grants-in-Aid for Scientific Research】

1. Scientific Research B "Research on Spectrum Sharing among Multiple Systems based on Correlation of Wireless Environment using Crowd Sensing"
   Takeo Fujii
2. Scientific Research Fostering Joint International Research Type B "Research of Smart Spectrum using Multi-dimensional Wireless Environment Recognition based on Learning"
   Takeo Fujii (PI belongs to other organization)
3. Scientific Research B "Research on Optically Powered Radio-over-Fiber systems"
   Motoharu Matsuura
4. Scientific Research A "Massive IoT Device Communications based on Belief Propagation Detector for Massive Overloaded MIMO Systems."
   Koji Ishibashi (PI belongs to other organization)

【Commissioned Research】

1. MIC "Dynamic Spectrum Sharing among Different Radio Services"
   Takeo Fujii, Koichi Adachi

2. MIC “Highly-Reliable Wireless Access Technology for Advanced 5G Networks”
   Koji Ishibashi
3. MIC SCOPE “Flexible LPWA Based on Environmental Dynamics”
   Koichi Adachi, Takeo Fujii
4. MIC SCOPE JP-EU Joint Research “5G Enhanced Mobile Broadband Access Networks in Crowded Environments (5G-Enhance)”
   Takeo Fujii, Koji Ishibashi, Koichi Adachi

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)
Associate Prof. Koji Ishibashi (Green network and communication theory)
Associate Prof. Ryo Ishikawa (RF energy harvesting)

2.4.3 Major Research Outcomes in 2020

[Development of RF Energy Harvesting System from Environment RF signal] (Koichiro Ishibashi Lab)

RF energy harvesting technology which could be inevitable for future Trillion Sensor Universe has been investigated in the division of Exploring Low Power Wireless. We have been investigating to harvest the energy from environmental RF signal so that every sensor node at environment can operate everywhere and every time. We have developed Energy Harvesting Rectenna from LTE Mobile phone Signal combined with Yagi Antenna(Fig. 2.4.1). The power obtained from the LTE mobile phone signal can be increased to 7.6uW(Fig. 2.4.2).

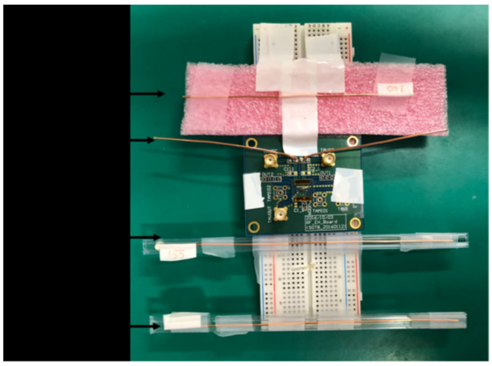


Fig. 2.4.1 Rectenna for 950MHz LTE signal for cell phone.

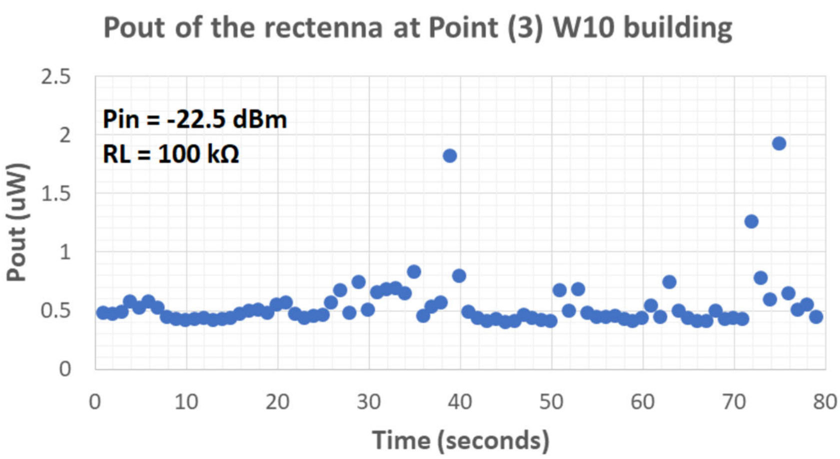


Fig. 2.4.2 Output power of the Rectenna.

【Grants-in-Aid for Scientific Research】

1. JST/CREST, "Scavenging nW RF energy using Super Steep Transistor and Meta-Material Antenna" (K. Ishibashi)

[Age of Information in Energy Harvesting Wireless Sensor Networks] (Koji Ishibashi Lab.)

In recent years, energy harvesting wireless sensor network (EH-WSN), which is equipped with energy harvesting (EH) technology that harvests power from natural phenomena such as sunlight and vibration, and aims for maintenance-free operation, has been studied. However, there is a limit to the average harvested power, and the problem is that the sensor node (SN) may not be able to transmit information at any given time due to power shortage. To address this problem, analysis based on the freshness of information (AoI: Age of Information) has been discussed. AoI is defined by the elapsed time from the generate time of observation information that fusion center successfully received to the present time. To the best of our knowledge, no mechanism to minimize the AoI in EH-WSN has been proposed thus far. Therefore, we investigated the AoI by focusing on time-division multiple access (TDMA) and frequency-division multiple access (FDMA) as grant access where N EH-SNs communicate simultaneously to a common FC. Moreover, we proposed novel resource allocation algorithms both in TDMA and FDMA to minimize the corresponding average aggregate AoI. Fig. 2.4.3 shows the average AoI per SN as a function of the size of data packets in TDMA and FDMA. From the figure, it can be seen that the grant access that achieves the minimum average AoI depends on the amount of data packets. From the above, it is necessary to choose TDMA and FDMA according to the conditions of the system. This result has been already published in IEEE journals.

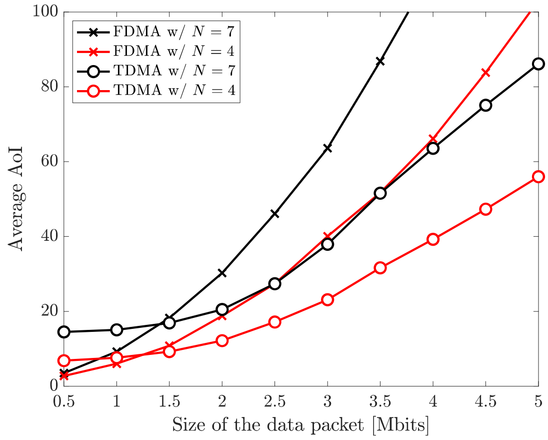


Fig. 2.4.3 Average AoI as a function of the size of data packets in TDMA and FDMA systems.

[Highly Efficient Encryption-then-Compression Technique Based on Packet Aggregation] (Koji Ishibashi Lab.)

Multi-hop transmission has emerged as a promising technique to address the need for high scalability and low power consumption in wireless sensor networks (WSN). Previously, MAC protocols that improve energy efficiency by operating each node intermittently were proposed, such as IRDT (Intermittent Receiver-Driven Data Transmission). However, in such a protocol, the bottleneck problem may occur when an intermediate sensor node (SN) has only a single connection with the destination or to a SN closer to the destination. One option to enhance the throughput at the SNs is the compression of multiple packets to forward. Nevertheless, this is unfeasible since the packets are encrypted at every SNs for privacy protection. In our work, we exploit the idea of the Slepian-Wolf theorem and propose the encryption-then-compression (EtC) scheme with packet aggregation, enabling the intermediate SNs to compress packets.

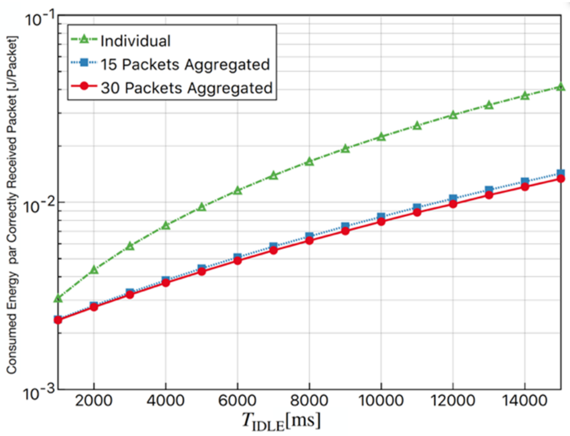


Fig. 2.4.4 Relationship between intermittent interval T_{IDLE} and average energy consumption of a node per correctly received packet.

Fig. 2.4.4 shows the relationship between intermittent interval and the average energy consumption of a node per a correctly received packet at the destination when each node communicates based on IRDT. The results shown in the figure indicate that, when T_{IDLE} is large, the IRDT using the proposed EtC method achieves lower energy consumption than the original IRDT.

[Wide-dynamic-range high-efficiency rectifier with zero-threshold GaAs HEMTs] (Ishikawa Lab.)

Middle- to long-range microwave wireless power transfer is promising candidate for wireless power supply applications, such as an emergency power supply. For these technologies, a rectifier is one of the key devices to convert RF power into DC power. However, the input power range with high-efficiency operation is narrow for conventional rectifiers. Since the input power largely varies in actual usage, a wide-dynamic-range high-efficiency characteristic is required for the rectifiers. We have developed a wide-dynamic-range high-efficiency rectifier configuration by using two types of transistor rectifiers with zero-threshold GaAs HEMTs. The high-efficiency operation is shifted to a higher input power region by decreasing the gate-bias voltage of the transistor rectifier, whose circuit is carefully adjusted. Thus, according to an input power increase, a suitable gate-bias voltage was supplied to the high-efficiency transistor rectifier from a transistor rectifier circuit generating a negative DC voltage. The fabricated rectifier with zero-threshold GaAs HEMTs exhibited RF-to-DC power conversion efficiencies of more than 60% and 70% for input powers from 0 to 25 dBm and 9 to 24 dBm, respectively, at 2.27 GHz. (Fig. 2.4.5)

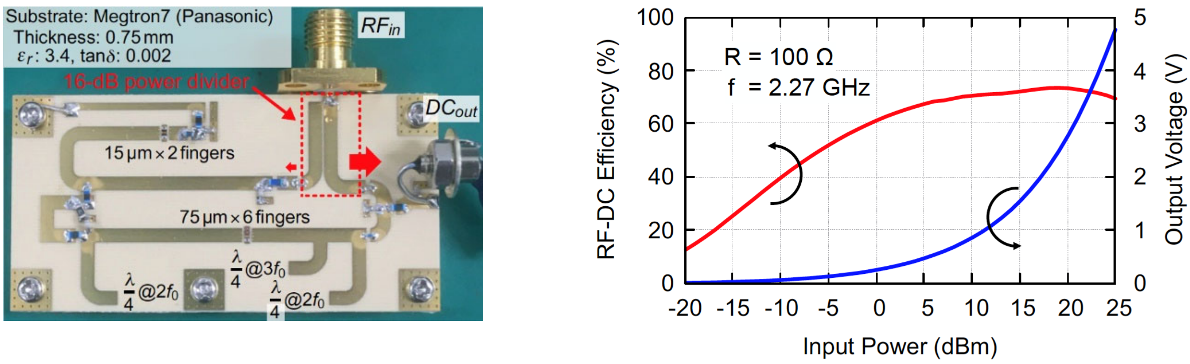


Fig. 2.4.5 Fabricated wide-dynamic-range GaAs HEMT rectifier, and its characteristic

【Grants-in-Aid for Scientific Research】

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

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

In mobile communications, the interruption is one of the serious problems, and occurs frequently due to natural disasters such as earthquake and tsunami. In particular, it is very important to survive base stations (BSs) in the event of disasters. Therefore, unmanned aerial vehicles such as drones have attracted much attentions, because these can be used as airborne BSs (ABSs) in such situations, instead of ground BSs. In order to realize ABSs, a few researchers have been focused on the use of drones. However, conventional drones for ABSs have drawback for practical use, because their batteries have the limitation of flight time and require the long charging time. To solve this problem, we have proposed the use of power-over-fiber that transmit the power required for driving drones into optical fibers. In this year, we present the flight control of an entry-type drone using an optical fiber without using wireless control signals. We show the flight demonstration of the drone by controlling a wired remote controller. Fig. 2.4.6 shows the electrical spectrum of the control signal after optical fiber transmission. The center frequency was at around 2.45 GHz. The inset shows the temporally waveform of the signal. It was a pulse train with the repetition rate, which coincide with the center frequency of the signal. To show the feasibility of the flight control of the drone using optical fibers, we executed the flight control demonstration of the drone, because we enabled to confirm the control signal after optical fiber transmission. The flying image is shown in Fig. 2.4.7. In this experiment, we demonstrated the flight control by using only optical fiber transmission in an environment where wireless communication between the drone and the remote controller (RC) was not possible. In this condition, after turning on the switch of the drone, the drone and the RC were synchronized, and the LEDs on the drone lighted up, the drone flighted. The driving voltage and current were 3.81 V and 1.12 A, respectively. The power consumption was 4.27 W. It should be noted that the black and red cables were not optical fibers, but electric wire cables. As the drone was too small to carry all the electrical equipment, these put on the ground, and connected to the drone using the electrical wire cable.

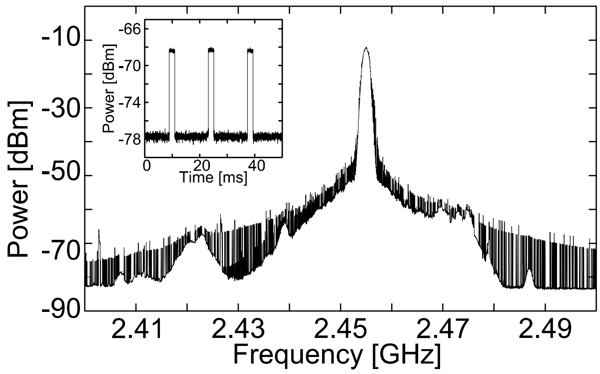


Fig.2.4.6 Control signal spectrum after optical fiber transmission, Inset shows waveform of control signal after optical fiber transmission.

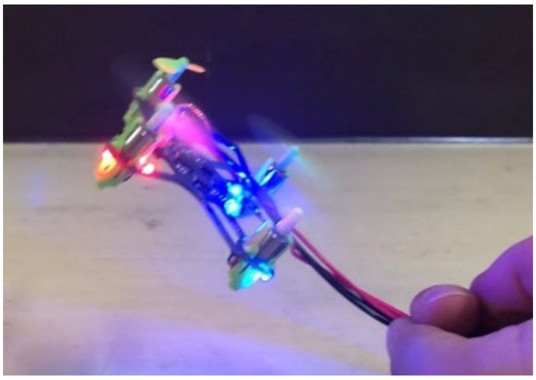


Fig.2.4.7 Flight control demonstration of drone using optical fibers.

[Channel Allocation for LoRaWAN Considering Intra-System and Inter-System Interferences] (Fujii Lab.)

In long range wide area network (LoRaWAN), which is one of the low power wide area network (LPWAN) systems, the number of LoRa nodes has been increasing rapidly. Additionally, although LoRaWAN uses the same frequency channels as other LPWAN systems, LoRa nodes randomly select channels for the uplink communications not considering the time occupancy of other systems. In such situations, intra-system and inter-system interferences are frequently occurred, which significantly deteriorates the communication quality. Thus, to suppress these interferences, it is necessary to accurately estimate the time occupancy in each channel and adaptively allocate LoRa nodes to channels based on the estimation results. Furthermore, because the time occupancy strongly depends on transmission duration, and signal power fluctuations owing to geographical conditions, the radio environment should be accurately predicted in advance. Therefore, we propose a channel allocation method based on the radio environment. First, the LoRa gateway (GW) observes the inter-system interference signals for a certain period and estimates an empirical cumulative distribution function (ECDF) of the time occupancy in each channel, as shown in Fig. 2.4.8. Based on the obtained ECDF, LoRa nodes are allocated to channels in ascending order of the time occupancy. Then, the GW reallocates the LoRa nodes to the channels searchingly based on the formula of intra-system interference probability so that the probability on each channel becomes lower than the threshold while maintaining the inter-system interference suppression. Fig. 2.4.9 shows the simulation results of the average packet loss rate (PLR), and it is confirmed that our proposed method can suppress the PLR compared to the conventional random channel selection.

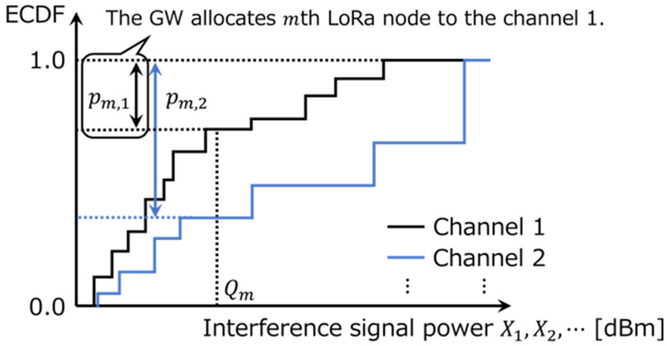


Fig. 2.4.8 Channel allocation based on the ECDF of the time occupancy of other systems.

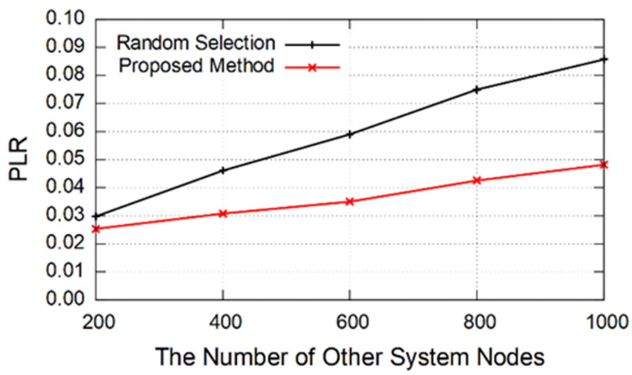


Fig. 2.4.9 Average PLR of LoRa nodes for the number of other system nodes.

【Cooperative Research】

1. "Scavenging nW RF energy using Super Steep Transistor and Meta-Material Antenna,"On JST/CREST "Scientific Innovation for Energy Harvesting Technology" (Koichiro Ishibashi, Ryo Ishikawa, and Koji Ishibashi)
2. "Optimization of Smart-Meter Networks" (Koji Ishibashi and Takeo Fujii)

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受賞

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【10】 片桐啓太、IEEE VTS Tokyo Chapter 2020 Student Paper Award、Nov. 2020.

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【22】 相楽昌希、フォトニックネットワーク（PN）研究会 若手研究賞、電子情報通信学会 フォトニックネットワーク（PN）研究会、Mar. 2021.

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特許

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