AWCC Advanced Wireless and Communication Research Center

Advanced Wireless & Communication
Research Center

ACTIVITY REPORT 2021

The University of Electro-Communications

Message from the Director, Prof. Takeo Fujii

Due to the impact of the Convid-19 disaster in 2021, AWCC research also continues to operate under restrictions. Under this situation, activities have gradually increased, including the start of hybrid research meetings in a remote and face-to-face. Although face-to-face participation in international conferences is still difficult, the entire research community is seeking post-corona activities, such as the resumption of on-site workshop in Japan. While the activities of Advanced Wireless Communication Research Center (AWCC) were slightly decreased comared with statistics of pre-corona, activities were improved including launching several national projects including beyond 5G, low power sensor networks and cooperative autonomous vehiles. 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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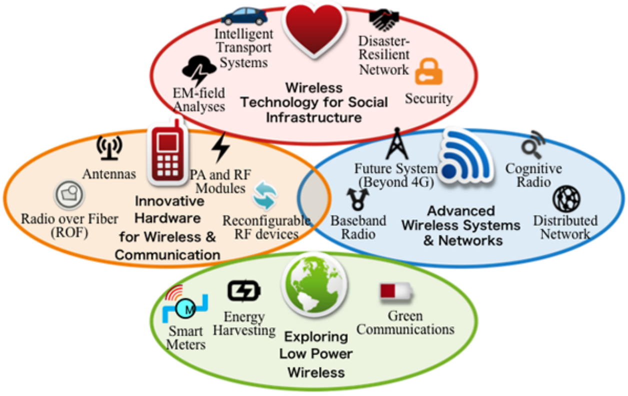
1 . ABOUT AWCC

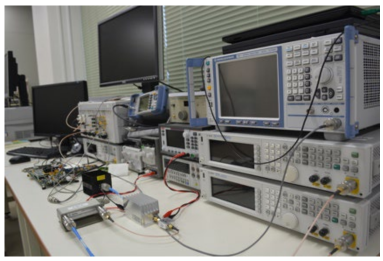
1.1 OVERVIEW



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

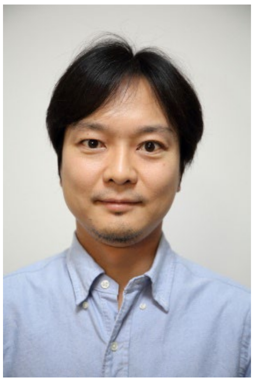
【Director, Full-time Prof. Takeo Fujii】

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 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 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 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.

【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. Yasushi Ito, Ph.D.

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

【Cooperative Professors】

Prof. Nobuo Nakajima, Ph.D.

Prof. Haruhisa Ichikawa, 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. 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.

【Visiting Professors from Industry】

Prof. Kunio Uchiyama (AIST)

Prof. Takahiro Asai(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 2021

(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."

[Constructing packet delivery rate-based map for V2X using confidence interval] (Fujii Lab.)

Recently, a radio map has been attracted attention for realizing reliable V2X communications. To create the radio map for V2X communications, each vehicle observes radio environment information, such as the received signal power, and reports the information to a cloud server. The cloud server constructs a radio map by processing the reported information. Communication parameters can be properly designed using a radio map because of the accurate estimation of radio propagation. However, an inaccurate radio map may be created in V2X communications owing to the small number of observation data. Thus, we propose a method to correct the statistical information of a radio map based on interval estimation. In the proposed method, the PDR of each mesh is corrected so that the lower confidence limit of the PDR is greater than an acceptable value using the Clopper-Pearson confidence interval, which is an interval estimation method of the population ratio. The calculated reliability of the corrected maps for the number of samples for each mesh gives an idea of how reliable each corrected mesh is, as Figure 2.1-1 shows (1-α is the confidence coefficient and β is the allowable absolute error). We will consider using this characteristic as a confidence criterion for the corrected PDR. In addition, from the simulation results assuming V2I communications shown in Fig. 2.1-2, it is confirmed that the proposed method (PDR_Conf) can guarantee the reliability of communications even under the sparse data constraint.

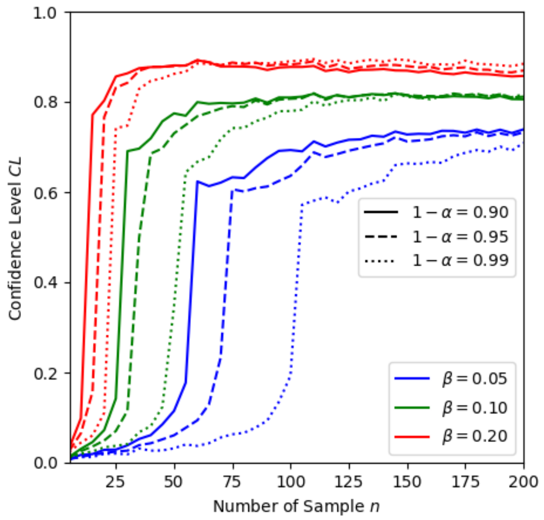


Fig2.1-1 Confidence level of the map for the number of samples in each mesh.

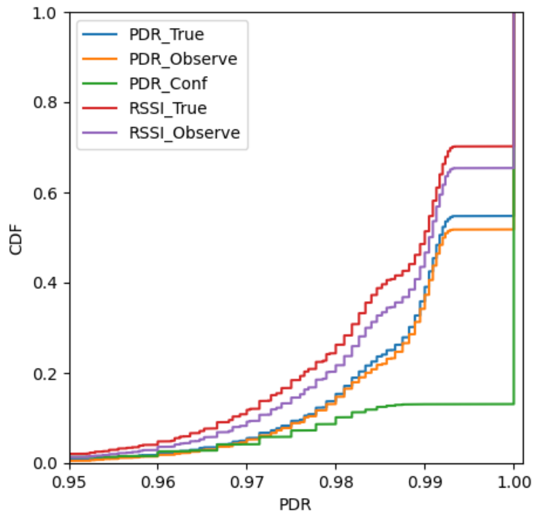


Fig 2.1-2 CDF of PDR in V2I communications ($1-\alpha=0.95$).

(B) Radar Signal Processing

[Vehicle Onboard Radar] (Inaba Lab.)

The stepped multiple frequency (SMF) modulation has proposed by Inaba Lab. 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. 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.

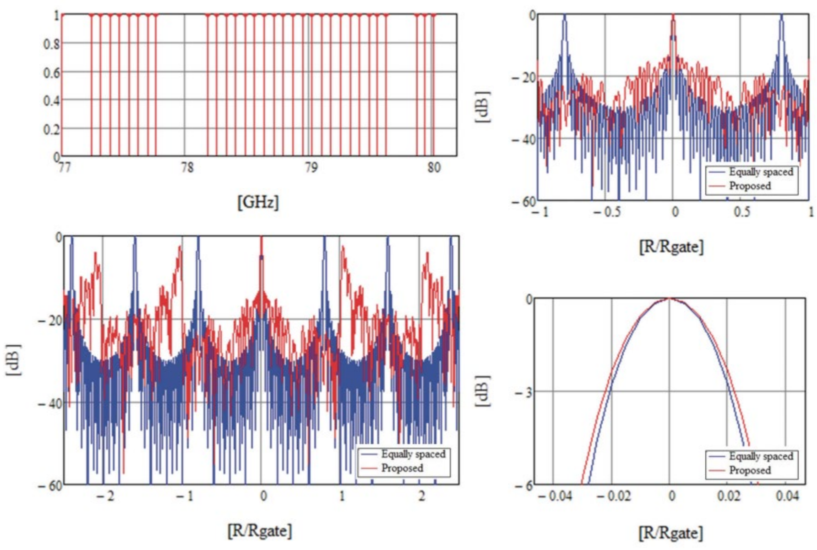


Fig.2.1-3 Output of the frequency vector by sparse frequency step design and Synthetic Wideband Waveform (Rate=0.8).

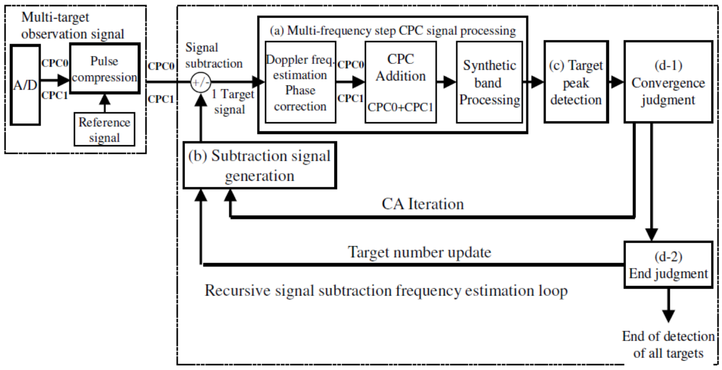


Fig.2.1-4 Block diagram of the signal processing of iterative signal subtraction and frequency estimation method in stepped multiple frequency radar.

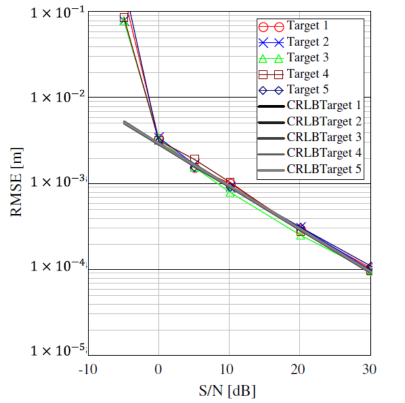


Fig. 2.1-5 Target range estimation RMSE and CRLB of the proposed method.

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 (shown in Fig. 2.1-3). The target range and velocity are obtained by the signal processing of iterative signal subtraction and frequency estimation (shown in Fig.2.1-4). Simulation results indicated that the RMSE of range of each target shows a good agreement with CRLB (shown in Fig.2.1-5). These proposed methods can not only detect the targets having different receiving signal level of power with the high resolution but also mitigate the multipath fading due to the ultra-wideband width.

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

【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”
   T. Fujii, K. Suto

【Cooperative Research】

1. “Research on improvement in recognition rate of RF IDs”
   Y. Yamao
2. "Research on communications technology for machine tools"
   K. Adachi and Y. Yamao

【Other Funds】

1. “Improvement of spatial resolution of radar sensor”, 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. 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 2021

(A) [Wide-dynamic-range GaN HEMT outphasing amplifier and quasi-millimeter-wave Doherty power amplifier MMICs] (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 MMIC exhibited a peak drain efficiency of 63% with a maximum output power of 35dBm at 4.6 GHz. In addition, a drain efficiency of more than 40% was maintained within an output back-off of 8 dB (Fig. 2.2.1).

In addition, a 28-GHz-band GaN HEMT MMIC Doherty power amplifier has been developed by using 0.15-µm GaN HEMT MMIC technology. The Doherty amplifier was designed by adaptively adjusting a load resistance division to a carrier amplifier (CA) and a peaking amplifier (PA) according to an output power balance between the CA and PA. The fabricated GaN HEMT MMIC Doherty amplifier exhibited a maximum drain efficiency of 54% and a maximum power-added efficiency of 44% at 29.1 GHz, with a saturation output power of 30 dBm. In addition, a drain efficiency of 33% was achieved at 29.1 GHz on a 9-dB output back-off condition (Fig. 2.2.2).

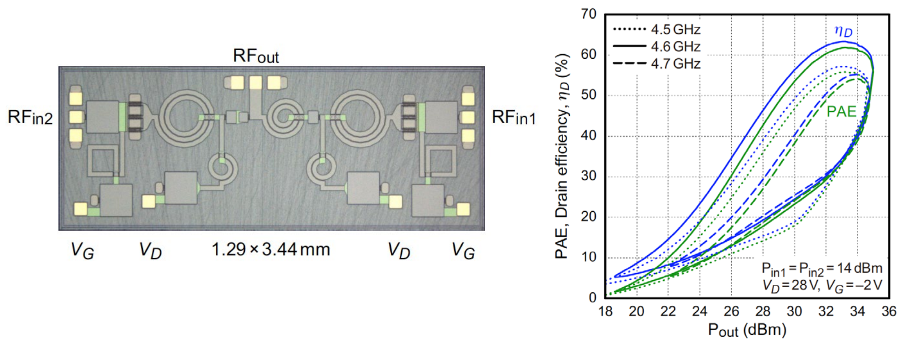


Fig. 2.2.1 Fabricated GaN HEMT outphasing power amplifier with a compact combiner, and its characteristics

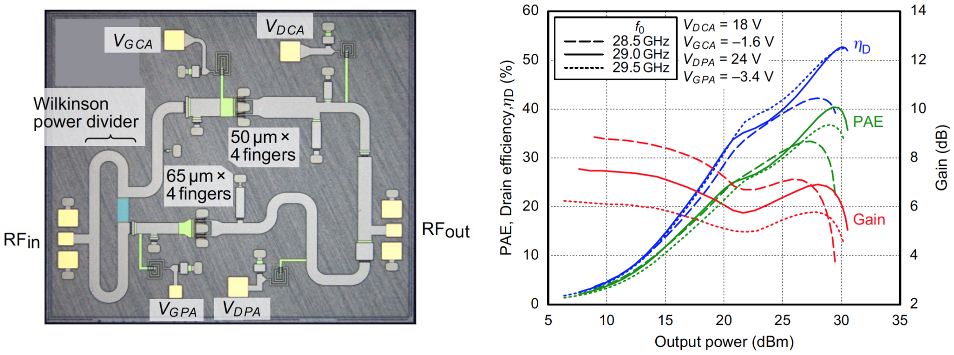
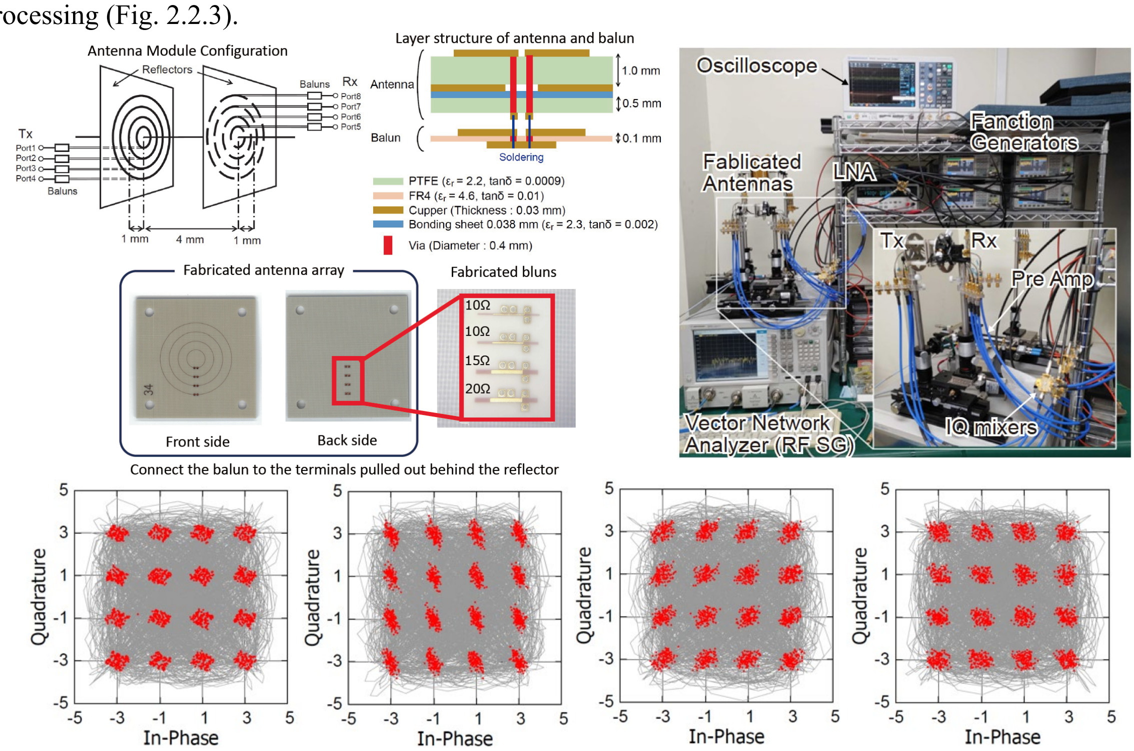


Fig. 2.2.2 Fabricated 28-GHz-band GaN HEMT Doherty power amplifier, and its characteristics

(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. In addition, the communication characteristics have been successfully improved by connecting baluns to the terminals of the integrated circular loop antenna at the back side of the reflector. The merchant balun serves as the impedance matching, and by using open-ended $\lambda/4$ lines as the ground of the balun, it could be arranged in a narrow space behind the reflector. In eigenvalue decomposition of the measured four-port S-parameters on the OAM communication between the fabricated loop antenna arrays, a transmission power of 98.9 % was treated as the eigenvalues without signal precoding, which indicated high mode purity. If a signal precoding is performed, all of transmission power (100%) is treated as the eigenvalues. In a four-channel 16QAM communication test for the loop antenna array systems, EVMs of less than 9.6 % were obtained for each channel without any signal processing (Fig. 2.2.3).



Mode 1 (Rx5) EVM: 9.5%, Mode 2 (Rx6) EVM: 8.6%, Mode 3 (Rx7) EVM: 9.6%, Mode 4 (Rx8) EVM: 9.6%

Fig. 2.2.3 Constructed 12-GHz-band 4-channel multiplexing OAM communication system, and its characteristics (12.44 GHz, 15.625 MSymbols/sec (Total: 250 Mbps), Tx1: 30 mV, Tx2: 30 mV, Tx3: 55 mV, Tx4: 30 mV)

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

Digital-to-analog conversion (DAC) is an essential function in a wide field, including communication networks. In recent years, with the development of analog and digital signal processing technologies, the demand for DACs with higher performance is rapidly increasing. However, electrical DACs have inherent bottlenecks such as jitter limitation, electromagnetic interference, and resistive-capacitive delay for higher speed operations. On the other hand, all-optical (photonic) approaches have attracted much attention recently, because photonic DACs enable us to overcome many bottlenecks of electrical signal processing. However, these photonic DACs have complicated schemes, and require any additional electrical signal components to perform the DACs.

Semiconductor optical amplifiers (SOAs) have practical advantages such as small footprint, low switching energy, high nonlinearity, and ability of monolithic integration for optical signal processing applications. In particular, quantum-dot SOAs (QD-SOAs) provide higher bit-rate operation and broader gain than those of conventional SOAs. Owing to these features, we have successfully achieved ultrahigh-speed optical signal processing using QD-SOAs. In SOAs and QD-SOAs, when an optical signal is amplified, red and blue frequency chirp occur at the leading and trailing edges of the signal pulse, respectively. Frequency chirp is well known phenomena with unique property. The peak values of red chirp (shift to longer wavelength side) strongly depend on the input signal power and the data pattern, and we have demonstrated a photonic analog-to-digital conversion using a red chirp in a QD-SOA. In contrast, the peak values of blue chirp (shift to shorter wavelength side) have low dependence on the input signal power and the data pattern. By utilizing this property, we have proposed a photonic DAC using a blue chirp in a QD-SOA. However, to improve the resolution and conversion speed of the photonic DAC, clock pulse trains with a shorter pulse width and much multiple wavelengths are needed for practical use.

In this year, we introduced a multi-wavelength clock generation using an optical comb generator (OCG) and 2-bit photonic DAC based on binary-to-quaternary conversion using a blue chirp in a QD-SOA. We experimentally demonstrated a 20-Gb/s DAC using the generated multi-wavelength clocks and evaluated the conversion performance.

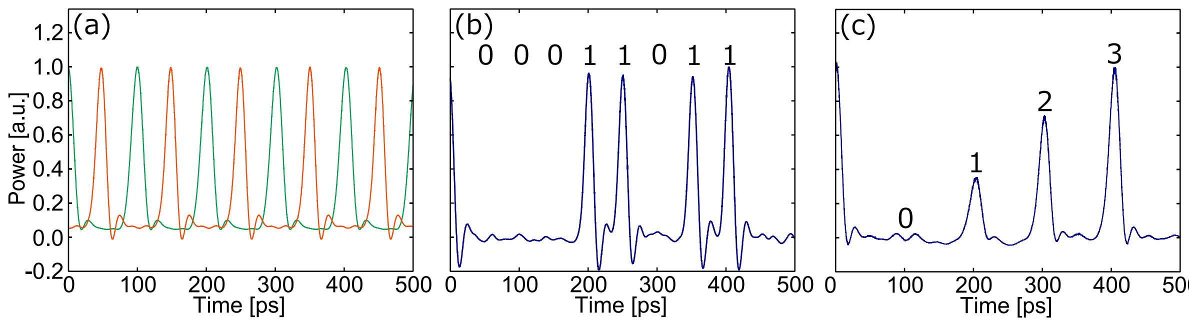


Fig.2.2.4 Examples of pulse trains of (a) 2-channel 10-GHz clocks with each different wavelength, (b) 20-Gb/s input binary data signal, and (c)converted signal when input binary data pattern was "00011011".

Figure 2.2.4 shows examples of the pulse train of the 2-channel 10-GHz clocks with each different wavelength, 20-Gb/s input binary data signal, and converted signal when input binary data pattern was "00011011". In Figs. 2.2.4 (b) and (c), it can be clearly seen that the 20-Gb/s binary-to-quaternary conversion was successfully achieved. It should be noted that we also achieved the binary-to-quaternary conversion with different binary data patterns. We also measured the amplitude accuracy of the output 4-level amplitude signal converted by the DAC. The output pulse amplitude is normalized by 4 steps, and the one step corresponds to the smallest increment step of the DAC output between two adjacent levels. The ideal DAC step is defined as one least significant bit (LSB). Based on this step, the differential non-linearity (DNL) and the integral non-linearity (INL) of the presented DAC were calculated. The DNL is defined as the deviation of the actual step from the ideal one, whereas the INL is defined as the deviation of the actual transfer function from the ideal one adjusted for the best-fit. The absolute values of the DNL and the INL were less than 0.13 LSB and 0.07 LSB, respectively. All the DNL values were within ±0.5 LSB, which provide no missing codes for the DAC. The INL values show that the maximum deviation from the ideal transfer function was 1.75%, which confirms that the DAC has high linearity.

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)

【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. ROHM Co., Ltd. "High frequency measurement technique for GaN-HEMT" (R. Ishikawa)
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) Examination of RF amplifiers for wireless power transmission in orbital solar power systems around the moon" (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. Koji Ishibashi (Future NW, Distributed NW)
Prof. Motoharu Matsuura (Future NW)
Associate Prof. Koichi Adachi (Future NW)

2.3.3 Major Research Results in 2021

[Local 5G mmWave Signal Measurement and Analysis for Spectrum Database] (Fujii Lab.)

The concept of the smart spectrum has been proposed to deal with the problem of shortage of spectrum. In smart spectrum, a database is constructed based on the measured data of the radio environment to manage the spectrum, thus realizing highly efficient spectrum utilization, and its usefulness has been confirmed in several systems. On the other hand, for 5G NR signals, the database based on the smart spectrum has not been studied and its usefulness has not been confirmed. In particular, since 5G millimeter wave (mmWave) signals adopt beamforming technology, it is necessary to estimate the directivity and propagation characteristics of multiple beams. Therefore, in the database construction, we need to measure and manage not only the conventional management for each base station and frequency but also each beam. In this study, we conduct a measurement campaign of mmWave signals from a local 5G base station in Imabari City, Ehime Prefecture, Japan, and construct a spectrum database. Additionally, based on the stored datasets, we show the results of analysis of the highest received signal power and its beam index in each beam at each location and comparison with propagation model.

A measurement campaign was conducted from Feb. to March 2021 to construct a spectrum database of mmWave signals of 5G NR. This campaign measured local 5G mmWave signals operated by Ehime CATV in Imabari City, Ehime Prefecture, Japan.

Based on the constructed spectrum database, the fluctuation graph of the highest average SS-RSRP among each beam index and its beam index is shown in Fig. 2.3-1 using a terminal's

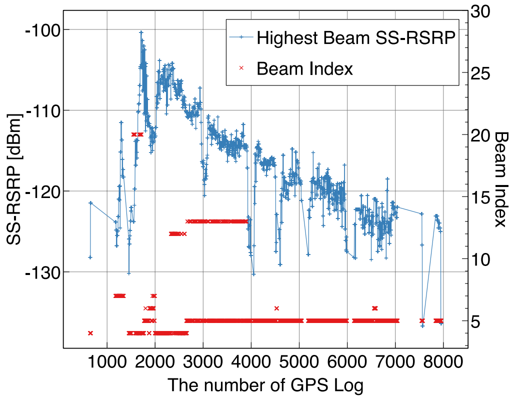


Fig. 2.3-1. Highest average SS-RSRP and index fluctuation in each beam index at each GPS log location.

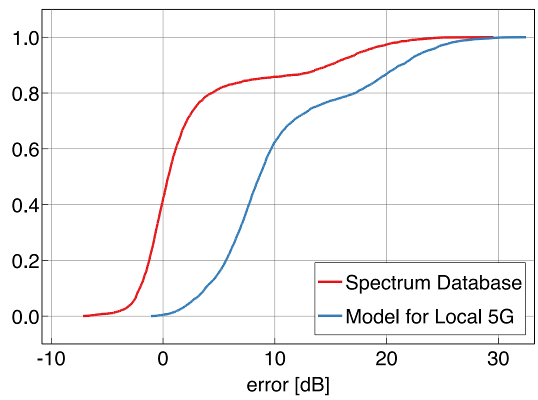


Fig. 2.3-2. Comparison of the CDF of the error between the database we constructed and the propagation model used for the local 5G license application.

GPS logs. Thus, the information on the fluctuation of the beam index of the highest SS-RSRP with the movement of the terminal is stored in the spectrum database, which can be applied to the control and management of each beam. Finally, the errors between the estimated values from the database and the propagation model and the true values are compared, respectively. As a comparison, we consider the propagation model used to calculate the coverage area in the local 5G license application. The cumulative distribution function (CDF) of the error in the estimate is shown in Fig. 2.3-2. This can be interpreted to mean that the local 5G coverage area by the propagation model is designed to be extra, which confirms the usefulness of the propagation environment estimation by the database.

[An Improvement of Security Scheme for Radio Environment Map under Massive Attacking] (Fujii Lab.)

Radio environment maps (REM) are widely used to enhance communication efficiency in spatial spectrum sharing. This can be generated using reports from the terminals. However, an open characteristic environment always leads to a security problem; for example, when malicious terminals exist in the environment and data falsification attacks occur, the accuracy of the REM is affected by the malicious action. We consider that malicious terminals exist in the communication environment, and they can attack the database to damage the accuracy of REM to satisfy their selfish requirements: affect the primary terminal frequency bands or take the free frequency bands, etc. REM construction need to collect received signal power from spatially distributed mobile terminals and calculate the average power of each mesh. Data falsification attack is an efficiency attack to damage the REM. This kind of attacks are also called Byzantine attacks, which refer to malicious terminals that change the data of their sensing power of the spectrum to blind the database (as Fig.2.2-3).

In this study, we improved the double-layer monitor algorithm to identify malicious datasets in the database. Additionally, we proposed a new algorithm involving interpolation based on spatial information to solve the problem of unequal information obtained from the meshes. By interpolation, a database can obtain sufficient datasets from each mesh and have a better performance (as Fig.2.2-4). Furthermore, we defined an optimal attack strategy using the proposed security algorithm. As Fig.2.2-5 shows, the influence of malicious terminals can be different when changing the attacking index. So, we can generate the optimal attack under the white-box mode. The simulation results indicate that the proposed method can eliminate the influence of malicious terminals and that a highly accurate REM can be obtained under even optimal attack (as Table2.3-1).

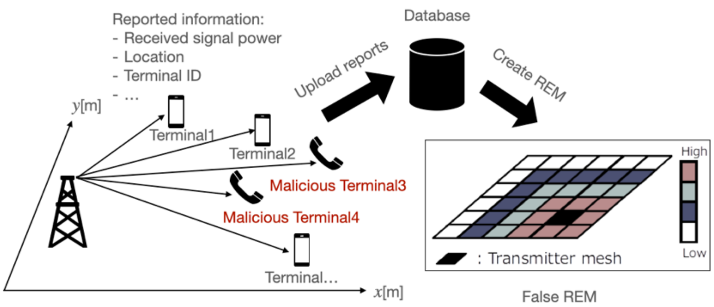
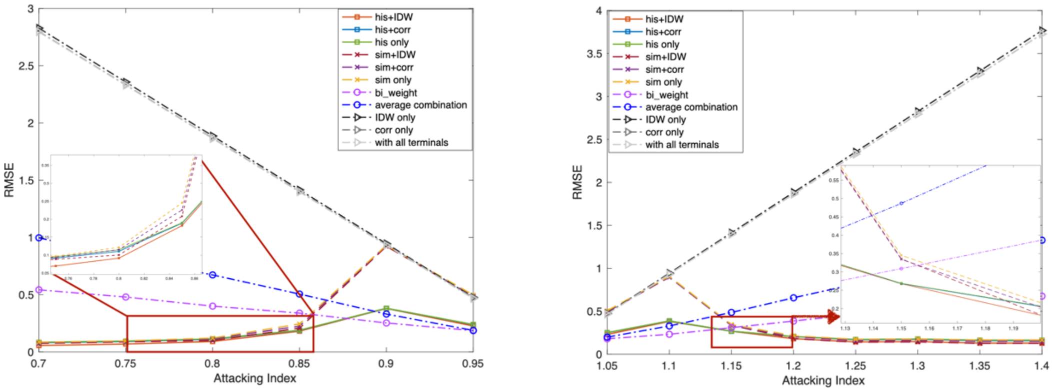


Fig. 2.3-3. A concept of the false REM.



(a) (b)

Fig. 2.3-4. RMSE under different attacking index.

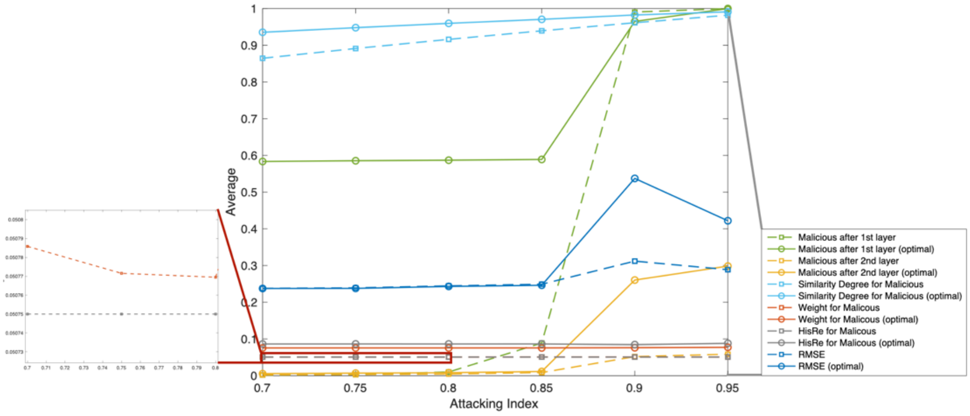


Fig. 2.3-5. Attacking performance under different attacking index.

Table 2.3-1. Accuracy index under optimal attack.

Attacking Index	error		
	optimal attack	traditional attack	
	proposed method	proposed method	with all terminals
0.85	0.0606	0.0621	**1.2877**
0.87	0.0867	0.0745	1.1160
0.90	**0.2888**	**0.0974**	0.8585
0.95	0.1781	0.0834	0.4292

[Radio Propagation Extrapolation by Using Multiple Separated Propagation Paths Estimated by Radio Map] (Fujii Lab.)

Nowadays, a radio map attracts attention to estimate radio propagation with high accuracy for sharing spectrum with multiple systems. In spectrum sharing, a secondary user (SU) must suppress own interference power toward a primary user to 10-20 [dB] lower than the noise floor. The prediction accuracy may be degraded because it is difficult to detect the received signal power below the noise floor. Although estimating radio propagation below the noise floor to meet this criterion, the SU may not use conventional radio maps which miss the interference power below the noise floor. Therefore, an extrapolation method for radio propagation below the noise floor is necessary.

In order to solve this problem, we propose a novel extrapolation method of radio propagation based on the separation of a propagation path. Proposed method considers the situation such as Fig 2.3-6. Under this situation, we can consider that the path loss and the shadowing characteristics are similar in this path even if transmitters A and B are different on the duplicated propagation path. This is because the geographical conditions are the same in the duplicated path. Proposed method estimates the received power of transmitter A below noise floor, utilizing the spatial correlation. The proposed method separately estimates path loss and shadowing and received power in target point O. In path loss estimation, a propagation path from transmitter A to point O is separated in two paths. path loss of each path is calculated from observable received power of the transmitter near each path. Besides, path loss model is based in linear regression. In shadowing estimation, shadowing of transmitter A and B have a correlation. In addition, shadowing empirically follows log-normal distribution with log mean 0 [dB]. Hence, shadowing of transmitter A is calculated as the mean value of a conditional lognormal distribution based on the known shadowing for the transmitter B.

To verify proposed method, we conducted an emulation-based performance evaluation using the datasets in a real environment. the datasets were measured around Chofu City in Tokyo, Japan. The proposed method was evaluated by the two methods that estimate only path loss (Proposed method w/ PL_{AO} w/o δ_{AO}) and estimate path loss and shadowing (Proposed method w/ PL_{AO} w/ δ_{AO}). Compared methods were Extended HATA, extrapolation by linear regression with only the datasets of transmitter A (Extrapolation w/ PL_{AB}). Fig. 2.3-7. shows radio maps of true map, the proposed methods and the compared methods. The results show that the proposed method can predict the radio map with higher accuracy than the other methods. For example, the proposed methods could estimate the high received signal power in the north and the low one in the south as with the true radio map.

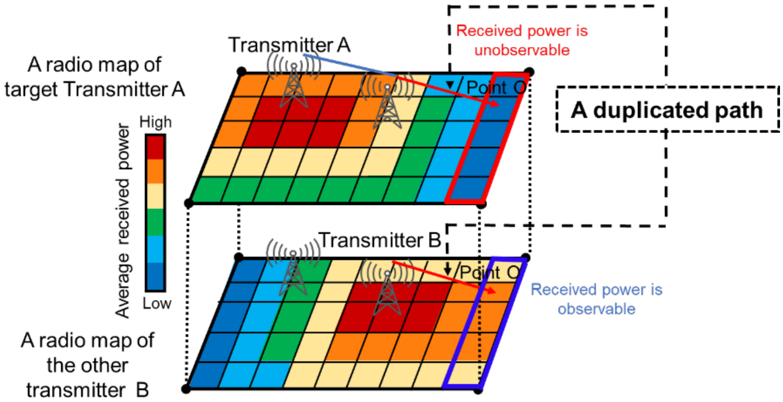


Fig. 2.3-6. Utilization of two radio maps.

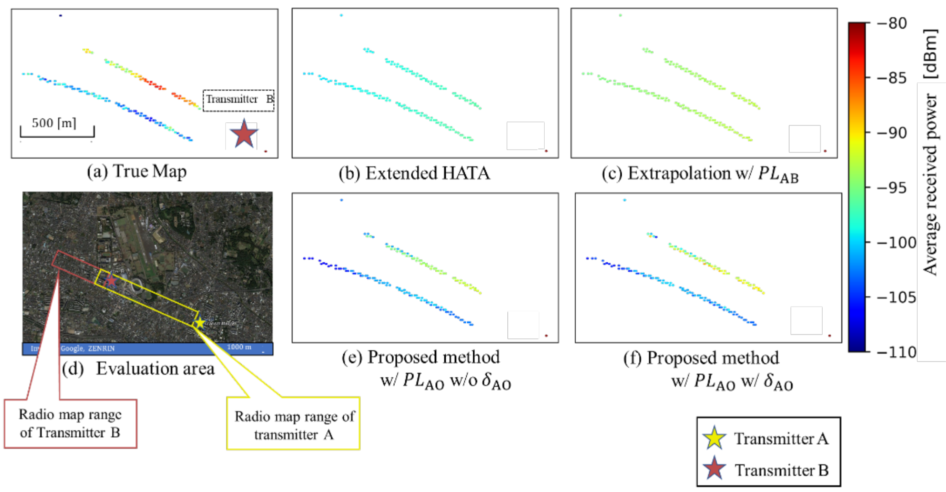
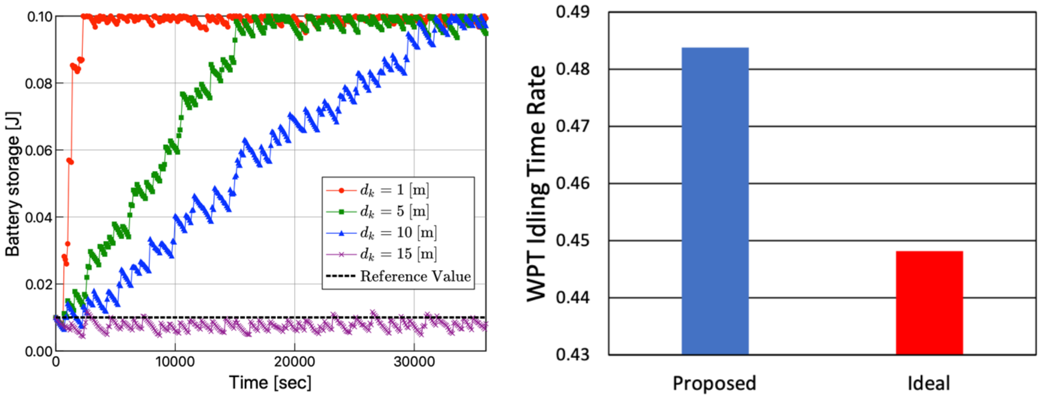


Fig. 2.3-7. An example of radio maps.

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

This research focuses on maintaining the battery storage 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 leads to power-saving and makes it easy to operate IoT sensor network. A centralized control at an access point (AP) can reduce packet collisions, but it incurs overheads by exchanging control information. Thus, we proposed a decentralized probabilistic binary offloading (PBO) strategy, which lets each WD probabilistically selects how to process computational tasks. However, the conventional PBO strategy did not consider the design of WPT transmission time and beamforming, and charged the batteries of WDs for the whole time at maximum power by WPT. Thus, this research proposes a dynamic offloading probability decision based on the battery storage at the WDs for the PBO strategy, an estimation method of the WDs' battery storage, and a design of the WPT beamforming duration.

This strategy can reduce overheads and WPT transmitting time. Fig. 2.3-8(a) shows the snapshot of the battery storage versus time when the number of the WPT transmit antennas is 16. It can be seen that the battery storage of the furthest WD, 15 [m], is maintained in keeping with the reference value, which is the value to charge up to this amount each time. Fig. 2.3-8(b) shows that the ratio when using the proposed method and the WPT designing with ideal knowledge of the battery storage of the WDs. The proposed method achieves about 48% of the time without WPT and extends that by about 4.5% more than the ideal case.



(a) Snapshot of battery storage (b) WPT idling time ratio

Fig. 2-3-8 Performance of proposed WP-MEC strategy.

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

We had previously proposed the concept of packet-level index modulation (PLIM) to increase the number of information bits transmitted by one data packet in low power wide area network. In PLIM, the generation interval between two consecutive packets is split into multiple time slots. Each EN transmits its packet in a specific combination of time slot and frequency channel, representing the index, to convey additional information bits. The gateway (GW) detects the time slot in which the data

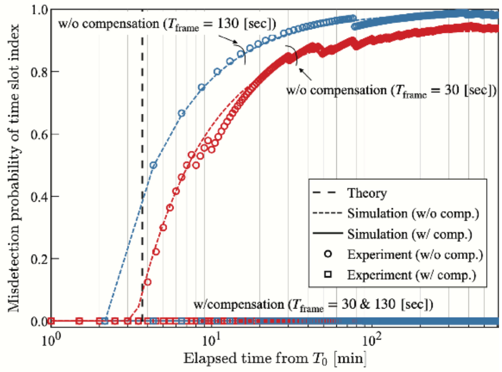


Fig.2.3-9 Misdetection probability of time slot index.

packet is being transmitted to retrieve additional information. Therefore, accurate synchronization between EN and GW is essential. However, clock drift occurs due to the inexpensive real-time clock oscillator on each EN, which results in timing misalignment between each node and the GW. We proposed a simple clock drift estimation & compensation method for the PLIM. Because EN and GW have common data for clock drift estimation, i.e., transmission interval, time slot length, and transmission timing offset, GW can estimate the amount of clock drift. The computer simulation results and experimental results in Fig. 2.3-9 indicate that the proposed clock drift estimation & compensation scheme enables the GW to detect the time slot index accurately even with the influence of clock drift. We have also implemented the proposed PLIM and clock drift estimation & compensation method in the commercially available LPWAN EN and GW as shown in Fig. 2.3-10.

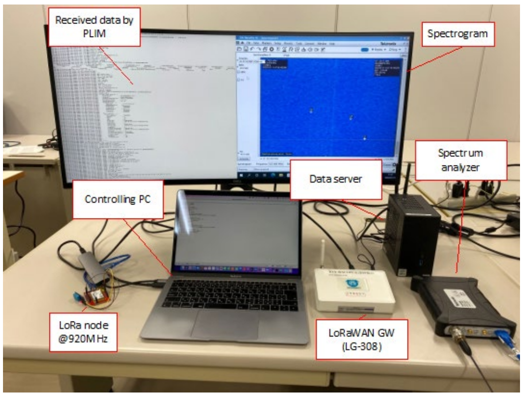


Fig.2.3-10 Implementation of PLIM.

To improve the performance of PLIM, we proposed an index mapping scheme. The conventional PLIM transmission could not fully utilize the available frequency and time resources. The proposed index mapping fully utilizes the available frequency channels and time slots to avoid packet collisions through simple index mapping and de-mapping. The proposed mapping does not require any information exchange between EN and GW except for the frequency channel allocation, which is currently available in LoRaWAN by default. Theoretical performance evaluation has shown that the proposed scheme improves the throughput performance by about 25% compared to the original PLIM transmission and significantly reduces overhead as shown in Fig. 2.3-11.

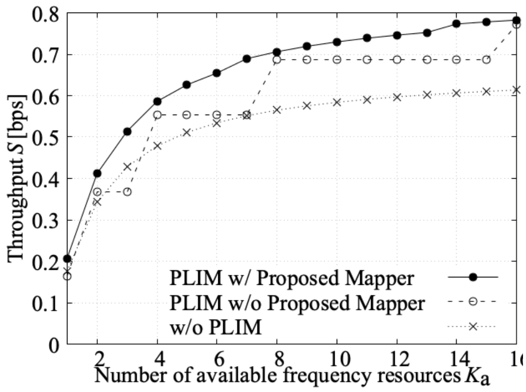


Fig.2.3-11 Theoretical throughput versus number of available frequency channels.

[Resource Allocation in LPWA] (Adachi Lab.)

Low power wide area networks (LPWAN) are attracting attention for their capability to realize a wide communication area of several kilometers at a low cost. To reduce the cost of nodes, LPWAN generally adopts the ALOHA protocol, a simple random-access protocol. However, the ALOHA protocol transmits packets at arbitrary timing, so as the number of nodes increases, the packet collision probability increases, and the packet delivery rate (PDR) of the system decreases. In industrial monitoring applications, the nodes sense the observation target periodically and transmit packets to the GW, resulting in periodic uplink traffic. Therefore, some combinations of packet generation cycles between nodes cause repeated packet collisions. To avoid repetitive packet collisions in an LPWAN with a large number of

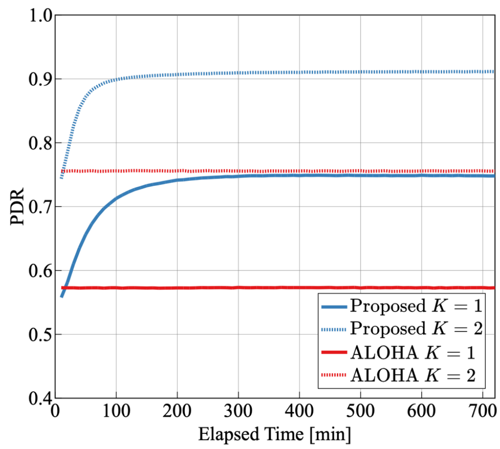


Fig.2.3-12 Time variation of PDR performance.

nodes and periodical traffic, we propose a centralized radio resource allocation scheme. The proposed scheme allocates an appropriate frequency channel and transmission offset time to each node using centralized control by the GW. The GW can predict the timing of a node's packet transmission based on the node's packet reception time and transmission cycle. Then, the GW estimates and compares the transmission timing of each node to predict packet collisions. The GW then calculates the offset time and frequency channel that can avoid packet collisions for the nodes for which packet collisions are predicted, and reallocates radio resources to the nodes using downlink. The performance evaluation considering the LoRaWAN network has been conducted. The computer simulation results show in Fig. 2.3-12 that the proposed scheme improves the PDR performance compared to ALOHA.

[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 large 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. 2.3-13. This academic year, we have proposed a GF-NOMA scheme without prior knowledge of the wireless channels, such as information on large-scale fading (LSF) coefficients. In this scheme, a multi-antenna BS estimates the active users and channels using the overlapped pilot signals spread over the time domain. It is done through a multiple measurement vector approximate message passing (MMV-AMP) with expectation-maximization (EM)-based hyperparameter update, i.e., EM-MMV-AMP. Fig. 2.3-14 shows the normalized mean squared error (NMSE) performance of GF-NOMA with the proposed algorithm. From the figure, the performance of our proposed scheme is comparable to conventional MMV-AMP with the perfect knowledge on LSF. Fig. 2.3-15 shows the miss detection (MD) probability and our proposed algorithm's false alarm (FA) probability with conventional and proposed decision rules. As seen from the figure, the FA probability of our proposed scheme with conventional decision rule remains significant high compared to that of conventional MMV-AMP. On the other hand, the proposed decision rule can lower both the probabilities of MD and FA even though BS does not know the LSF coefficient. This result has

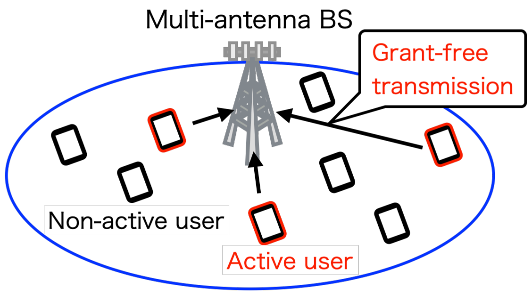


Fig. 2.3-13 GF-NOMA system

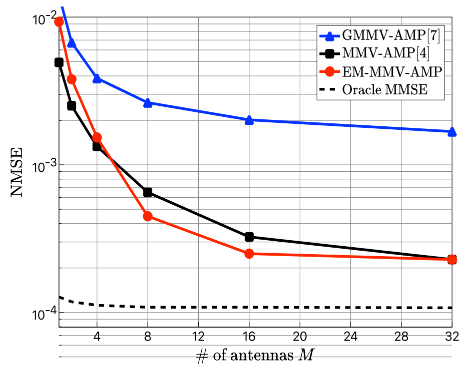


Fig. 2.3-14 NMSE performance of the proposed GF-NOMA scheme.

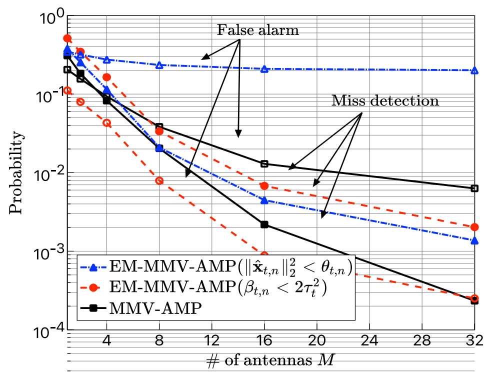


Fig. 2.3-15 MD and FA probabilities of the proposed GF-NOMA.

already been accepted for publication on IEEE journal.

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

Massive MIMO (mMIMO) systems will provide enormous degrees of freedom and are considered as a driver of the next generation of wireless systems such as Beyond 5G and 6G. Recently, cell-free mMIMO (CF-mMIMO) systems consisting of spatially distributed access points (APs) are actively discussed in order to make full use of the capability of mMIMO systems and address the limitation due to spatial correlations, as shown in Fig. 2-3-16.

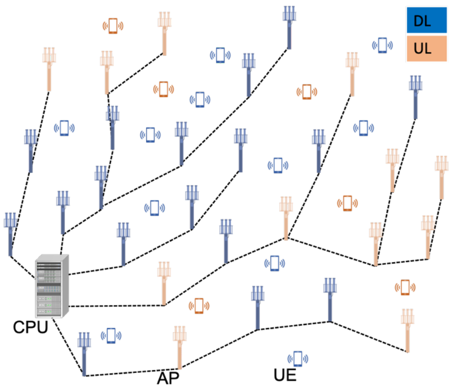


Fig. 2.3-16 Illustration of CF-mMIMO with dynamic TDD

However, the duplex and its corresponding beamforming (BF) design for CF-mMIMO have not been studied considering total throughput and user fairness for mixed uplink and downlink users. To this end, we proposed the resource allocation and BF design for the CF-mMIMO system with dynamic TDD using Lagrangian dual transform (LDT) and quadratic transform (QT). Figure 2.3-17 and Figure 2.3-18 show our proposed methods' total and worst-case spectral efficiency (SE). The proposed method using dynamic TDD outperforms the conventional method in both results. In particular, the design method using the geometric mean of throughput shows the highest performance in both the total and worst-case results. The results indicate that the system's proposed method achieves overall system performance and user fairness. These results have already been reported in the domestic conference and will appear in IEEE Access.

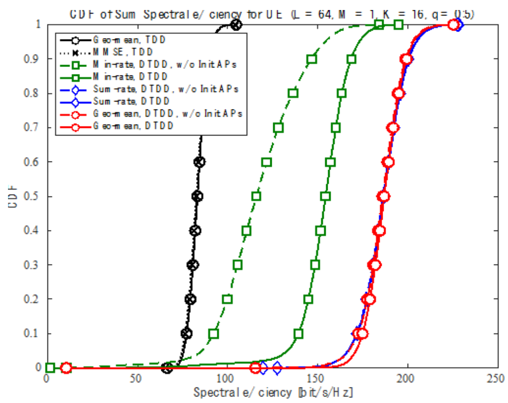


Fig. 2.3-17 CDF of the sum SE for the proposed and conventional BFs in dynamic TDD.

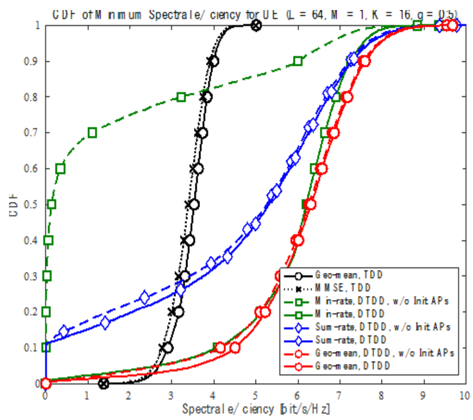


Fig. 2.3-18 CDF of the worst SE for the proposed and conventional BFs in dynamic TDD.

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

Millimeter-wave (mmWave) communications will play a key role in Beyond 5G and 6G wireless systems while their inherent vulnerability due to random path blockages in practical environments as shown in Fig 2.3-19 must be overcome. Several robust beamforming design methods and various blockage prediction methods have been proposed. However, several practically important questions still remain: what kind of information should be predicted, how accurate the prediction needs to be, and how such blockage-related information should be exploited. To this end, we evaluate the communication performances of various blockage-robust approaches based on the blockage model obtained by the experimental measurements. Figure 2.3-20 shows the achievable throughput of some blockage-robust approaches. In this figure, sum-rate maximization (SRM)-based coordinated multipoint (CoMP) transmission approaches with and without instantaneous block detection and our proposed outage minimization (OutMin)-based CoMP transmission with blockage probability prediction are presented. Surprisingly, the performance of "OutMin" is superior to "SRM (LOS RUs)" that only uses the radio units (RUs) in line-of-sights for transmission even though "OutMin" only uses the knowledge of the blockage probabilities. Moreover, it approaches the performance of "SRM (Perfect CSI)" that uses the perfect knowledge of the channel realizations. These results have been already reported in the domestic conference and will appear as an IEICE invited paper.

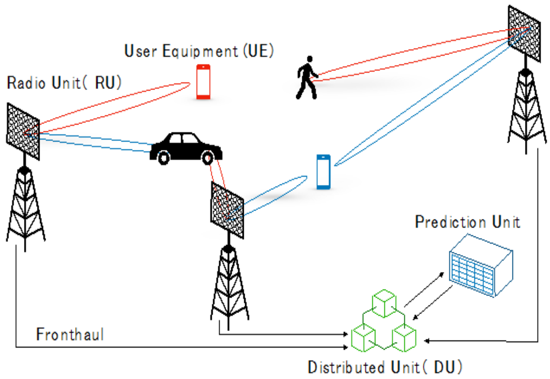


Fig. 2.3-19 System model of CoMP millimeter-wave communications with random blockages.

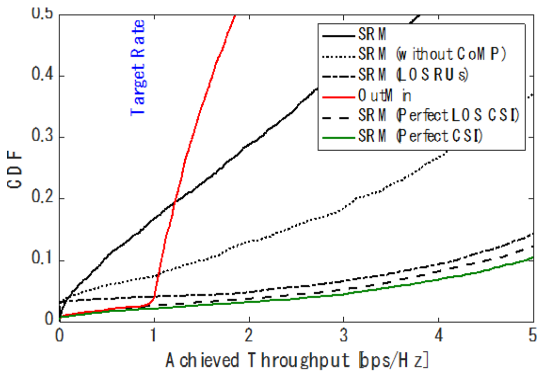


Fig. 2.3-20 CDF of achievable throughput of blockage-robust approaches.

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

Simultaneous over 40-W electric power and optical data transmission using an optical fiber is demonstrated for optically powered remote antenna units (RAUs) in future mobile communication networks. In this year, to further increase the delivered electric power by power-over-fiber (PWoF) link using a double-clad fiber, we improve the link design to extract a higher feed light power from the double-clad fiber output. Furthermore, to increase the electric power for driving RAUs, we employ a specially customized photovoltaic power converter (PPC) that directly converts optical power into electric power. The PPC can input a feed light with power of over 20 W and has a high optical-to-electrical conversion efficiency of over 50%. As a result, the combination of the improved PWoF link design and the use of the PPC successfully achieves the electric power delivery of up to 43.7 W. This is the highest electric power delivery demonstration by PWoF with optical data signals using a single optical fiber, to the best of our knowledge.

To evaluate the power transmission performance, we measured the delivered electric power and power delivery efficiency of the PWoF scheme, as shown in the left side of Fig. 2.3.21. Here, the power delivery efficiency is defined as the power ratio between the total feed light power injected into the PWoF link and the total electric power converted by the PPC. As the total feed light power increased, the delivered electric power was linearly increased up to 43.7 W. The linear characteristics are very useful for controlling the electric power supplied to the RAUs. The power delivery efficiency was almost constant regardless of the feed light power, and the average efficiency was approximately 30%. The improved PWoF design and the high-performance PPC greatly contributed to an increase in the delivered electric power of the PWoF link. The right side of Fig. 2.3.21 shows variations in the error-vector magnitude (EVM) penalties to the back- to-back signal of the simultaneously downlink- and uplink- transmitted data signals with the total feed light power injected into the PWoF link. In the both cases, the EVM values were almost constant, and the variations were less than 0.05% even when the feed light power was increased up to 150 W. The insets show the constellations of these signals when the feed light power was set to 150 W. The EVM values of the downlink- and uplink-transmitted signals were 0.79% and 0.83%, respectively. The result shows that these signals have good transmission performances even when electric power greater than 40 W is simultaneously delivered into the same optical fiber.

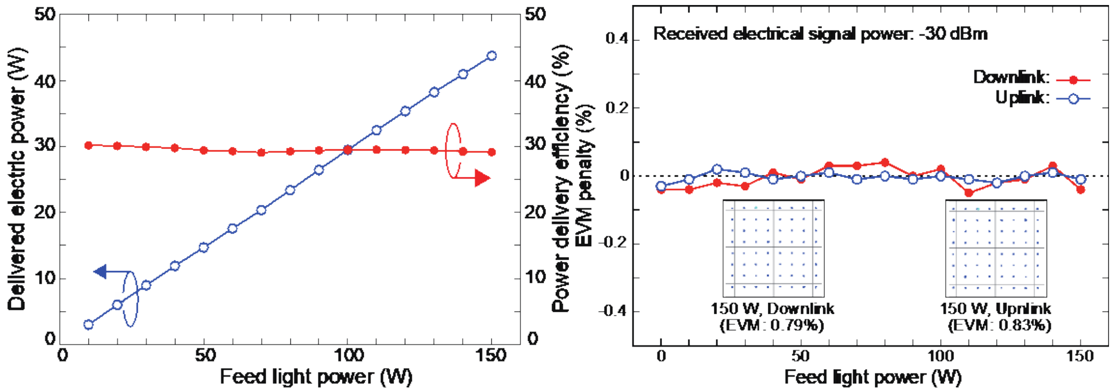


Fig.2.3-21 (Left) Delivered electric power and power delivery efficiency of PWoF scheme as a function of total feed light power injected into PWoF scheme. (Right) EVM penalties to back-to-back signal of downlink- and uplink-transmitted data signals as a function of total feed light power injected into PWoF link. Insets show constellations of downlink- and uplink-transmitted data signals with 150-W PWoF feed.

2.3.4 Funds

【Grants-in-Aid for Scientific Research】

1. Scientific Research B “Sensor Networks with High Speed Environmental Adaptation by Recognition of Synthesizing Wave”
   Takeo Fujii (PI belongs to other organization)
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)

【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. JST EIG CONCERT Japan " Organically Resilient and Secure Wireless Networks for Next-Generation IoT Technologies (ORACLE)"
   Koji Ishibashi

【Cooperative Research】

1. KDDI Research Inc., Motoharu Matsuura
2. NEC Corporation, Takeo Fujii
3. KDDI Research Inc., Koji Ishibashi
4. Ericsson AB, Koji Ishibashi

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 2021

[Development of 14nW Ultra Low Power Sub GHz Wake up Receiver] (Koichiro Ishibashi Lab)

By introducing wake up receiver (WuRx) in which a IoT system starts operating, the system can reduce power consumption significantly. In Koichiro Ishibashi laboratory, a study to realize Sub GHz WuRx was developed. By introducing pseudo Balan and ED first architecture without LNA and mixer, the power consumption of WuRx itself can be reduced. The WuRx was designed and fabricated using TSMC 65nm CMOS technology, and the fabricated chip generates wake up signal at 995 MHz with 14nW power consumption.

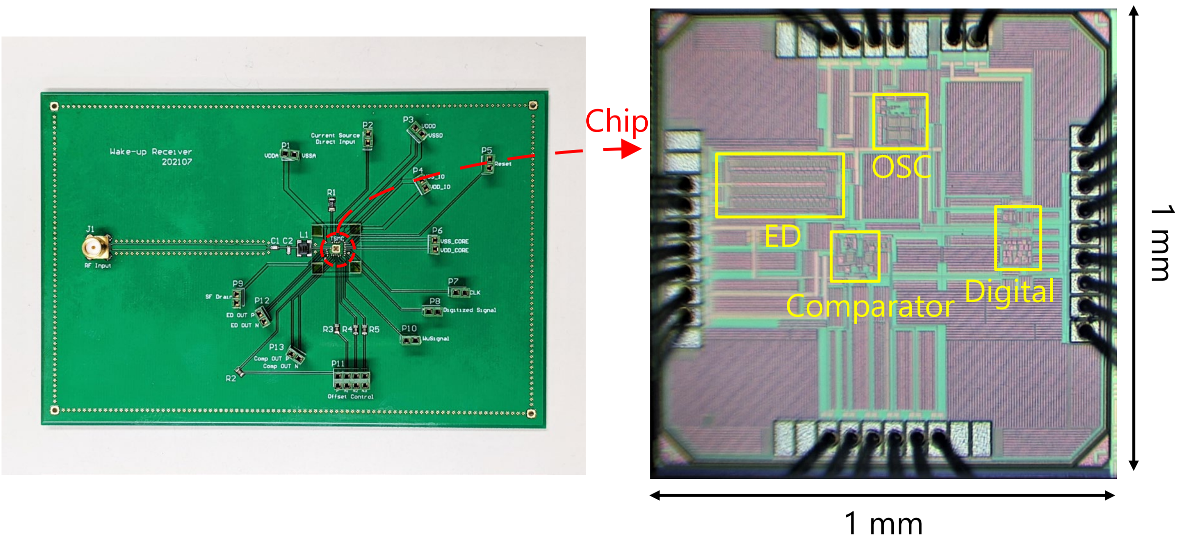


Fig. 2.4.3.1 PCB board and fabricated chip using TSMC 65nm of the WuRx.

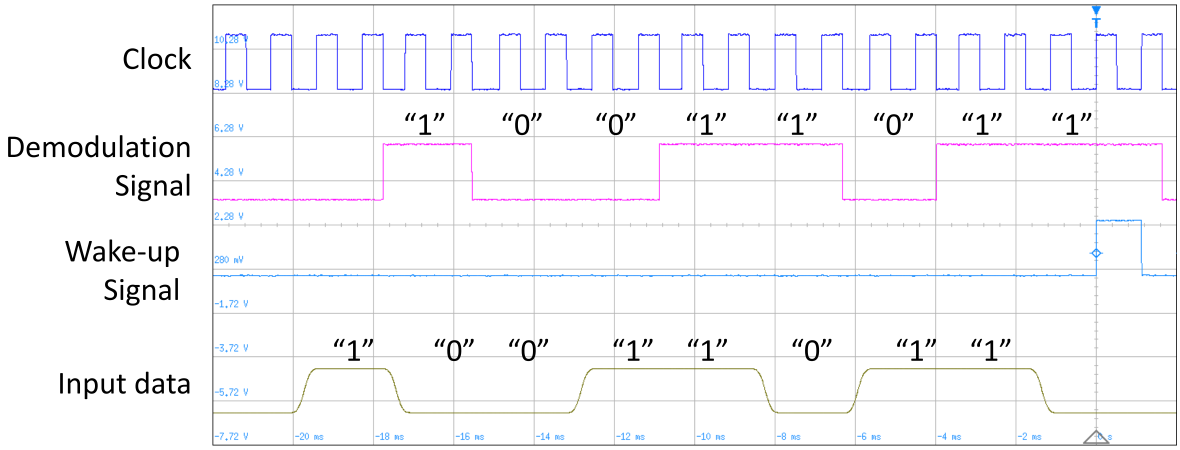


Fig. 2.4.3.2 Operating wave forms of the WuRx. Wake up signal is successfully generated after receiving the demodulation signal.

【Grants-in-Aid for Scientific Research】

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

[Encryption-then-Compression Technique Based on CRC-Aided Polar Codes for Highly Efficient Multi-Hop Transmission] (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). In intermittent receiver-driven data transmission (IRDT) protocol enabling multi-hop transmission, when an intermediate sensor node (SN) has only a single connection, this is called the bottleneck problem. An option to enhance the throughput is compressing the packets at the SN as the bottleneck. However, this is unfeasible due to the encryption of packets for privacy protection. In the last year, we have proposed the encryption-then-compression (EtC) scheme based on low-density parity-check (LDPC) codes with a belief propagation algorithm (BPA), enabling the intermediate SNs to compress the encrypted packets. This approach has a practical limitation in its compression rate and exhibits a performance gap from the theoretical limit.

To this end, we propose a rate-compatible compression method based on Polar codes with cyclic redundancy check (CRC) and a decompression method based on a successive cancellation list (SCL) decoding with the aid of CRC.

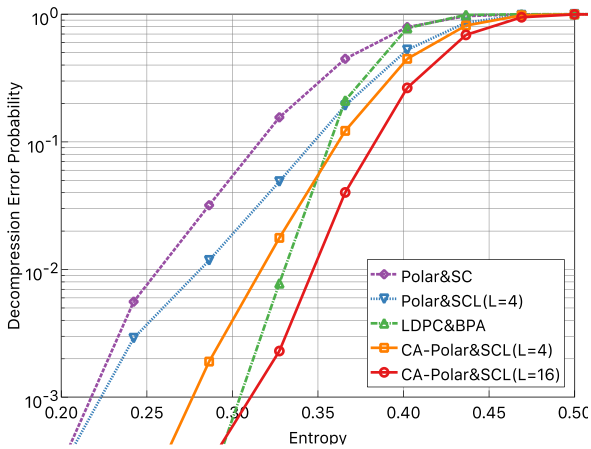


Fig. 2.4.3.3 Decompression performances of different EtC schemes.

Figure 2.4.3.3shows the decompression error probabilities of conventional and proposed EtC schemes for different entropy of packets. As clear, the proposed method (CA-Polar&SCL) with the number of lists $L = 16$ achieves the lower decompression error probability than the other EtC methods.

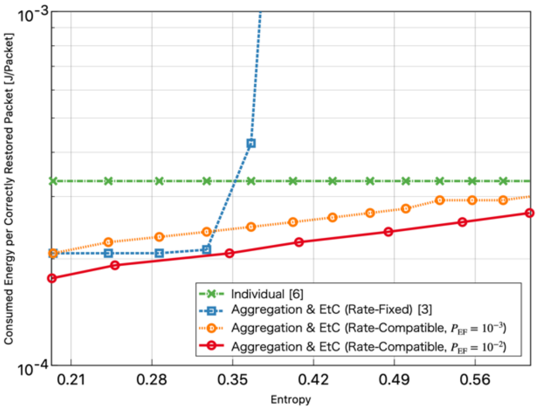


Figure 2.3.4.4: Energy consumption with different EtC schemes

Figure 2.4.3.4 illustrates the relationship between the given entropy and the average consumed energy. In the figure, “Individual” aggregation and EtC, “Aggregation&EtC (Rate-fixed)” is the case using the packet aggregation and EtC with the conventional method with the half compression rate, and “Aggregation&EtC (Rate-Compatible)” shows the proposed approach with $L = 16$. When the error free decompression is assumed as $P_{EF} = 10^{-2}$, the proposed method exhibits the lower energy consumption per packet at any given entropy compared to all other methods.

[A 10-MHz-Band Bidirectional Wireless Power Transfer System with Zero-Threshold Si MOSFETs] (Ishikawa Lab.)

A bidirectional wireless power transfer system via magnetic coupling has been developed at 10-MHz band by using high-efficiency DC-to-RF/ RF-to-DC power conversion modules and matched transmitter (Tx) and receiver (Rx) coils. The power conversion module is designed based on an operation similarity between transistor amplifier and rectifier, so it operates as an amplifier for converting a power from DC to RF and also operates as a rectifier for converting one from RF to DC. The module has same drain-side circuit with a harmonic reactive termination to obtain higher efficiency, and the gate-side circuit was adjusted to maintain the high-efficiency operations for both DC-to-RF/ RF-to-DC operations. In addition, by using a zero-threshold voltage transistor, a gate bias supply is not required. As the Tx and Rx coils are matched, they can transfer RF power bidirectionally with high efficiency. The constructed system with an RF frequency of 10 MHz achieved a maximum DC-DC conversion efficiency of 43% at a wireless distance of 3 to 6 mm (Fig. 2.3.4.5).

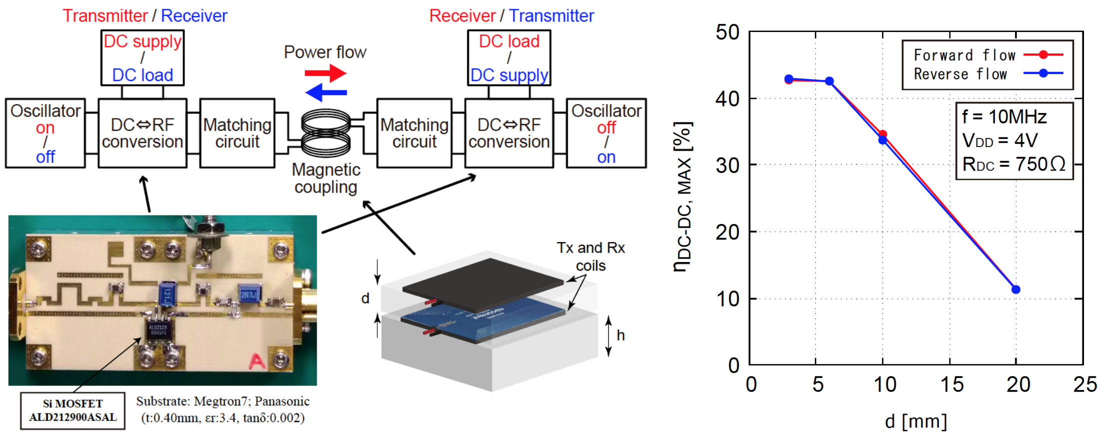


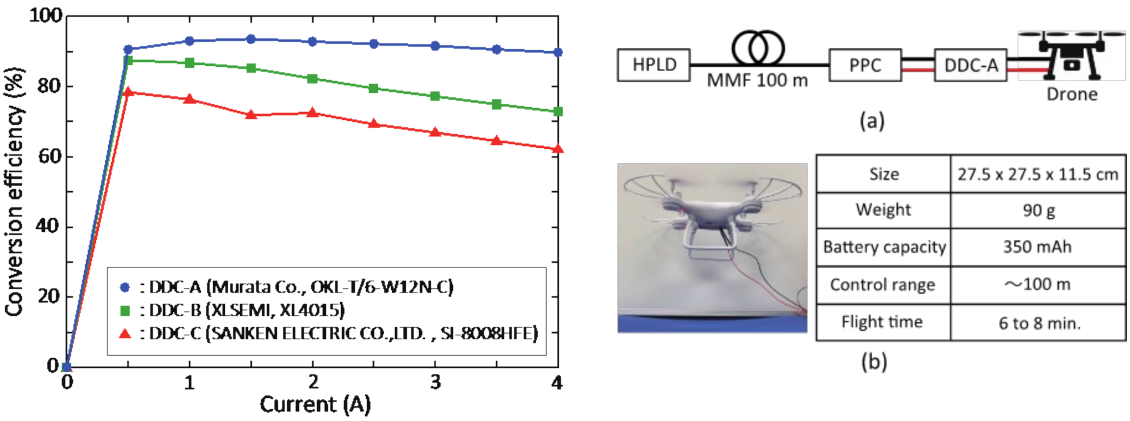
Fig. 2.3.4.5 Fabricated bidirectional wireless power transfer system, and its characteristic

【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)

In today's society, mobile communication has become an indispensable infrastructure, and it is important to ensure the continuous availability of services even in the event of a disaster such as a major earthquake. A base station is a critical communication link equipment that communicates directly with mobile terminals. However, when a disaster strikes and a base station is damaged, the terminals cannot be used in the cell area of the base station. In order to solve this problem, the use of aerial base stations is attracting attention as a temporary alternative. Unmanned aerial vehicles (UAVs) are being considered as aerial base stations. In particular, the use of drones is one of the most versatile options. However, as conventional drones are powered by batteries, their flight time is limited, making it difficult to operate them continuously as aerial base stations. For this reason, the use of long wires from a ground power supply is considered. Drones with wired power supply using metal cables have already been commercialized. However, there are concerns about hazards and damage from electric shock and lightning strikes. In contrast, we have proposed optically powered drone for aerial base stations driven by power-over-fiber (PWoF), and reported the flight demonstration of an entry-type drone and data and control signal transmission performance of the system, not including the flight demonstration.

In this year, we increased the feed light power of PWoF, and investigate the current and voltage characteristics of DC-DC converters (DDCs). By using the optimized DDC and a specially customized photovoltaic power converter (PPC), we reported a flight demonstration of a drone that is much larger than that of our previous work.



Size	27.5 x 27.5 x 11.5 cm
Weight	90 g
Battery capacity	350 mAh
Control range	～100 m
Flight time	6 to 8 min.

Fig.2.3.4.6 (Left) Conversion efficiency of three DDCs for various currents. (Right) (a) Experimental setup. (b) photo of flight demonstration and basic specification of drone. MMF: Multimode fiber, DDC: DC-DC converter.

The left side of Fig. 2.3.4.6 shows the DC-DC conversion efficiencies of three commercially available DDCs for various currents. In this measurement, the voltage was set to 3.7 V, which was optimal for driving the drone. As shown in the left side of Fig. 2.3.4.6 DDC-A had the highest DC-DC conversion efficiency at all currents. Thus, DDC-A was used in the following flight demonstration.

We conducted flight experiment using the DDC-A and the commercially available drone. The experimental setup is shown in the right side (a) of Fig. 2.3.4.6 To obtain higher electric power, we used a specially customized GaAs-based PPC based on the vertical epitaxial monolithic heterostructure architecture design. The device provides higher capability both of O/E conversion efficiency and available input optical power than those of conventional PPCs. The insertion loss of the 100 m multimode fiber (MMF) was 1.2 dB. The power injected into the PPC and the O/E conversion efficiency were 25 W and 56%, respectively. To drive the drone, the PPC output voltage of 6.4 V was converted into 3.7 V by the DDC-A. It should be noted that the PPC and DDC could not be loaded on the drone, and only the drone itself was flown. The right side (b) of Fig. 2.x.2 shows the photo of the flight demonstration and the specification of the drone we used. By in-creasing the feed light power with the PPC and DDC-A, we successfully achieved a flight demonstration of the drone that is over 11 times heavier and 36 times larger than that of our previous work.

2.4.3 Major Research Outcomes in 2021

[Successive Interference Cancellation Among Multiple LPWA Systems]（Fujii Lab.）

Nowadays, with the rapid development of Internet of Things (IoT), the number of low power wide area (LPWA) nodes that can communicate over long distances with low power has been increasing rapidly. Additionally, according to the IoT applications, multiple LPWA systems with different communication methods have been developed (e.g., long range wide area network (LoRaWAN), wireless smart utility network (Wi-SUN)). Because these systems are allocated to the same 920 [MHz] band and gateway (GW) of an arbitral system cannot demodulate signals of the other systems, inter-system interferences have been a crucial issue in addition to intra-system interferences. For the intra-system interferences, successive interference cancellation (SIC) for LoRaWAN has been proposed. In the SIC process, first, the long range (LoRa) GW accumulates the received signals. Then, the GW demodulates the signals in descending order of the received power. After that, the GW modulates the obtained data again and decreases the modulated signal from the accumulated signals. Finally, the GW demodulates the accumulated signals sequentially, which enhances the demodulation quality of LoRa signals. However, in this method, the inter-system interferences have not been considered, which may deteriorate the demodulation quality of LoRa signals remarkably because the LoRa GW cannot demodulate and decrease the signals of the other systems. Thus, we propose the SIC among multiple LPWA systems. Fig. 2.3.4.7 shows our system model. In our research, it is assumed that the LoRa and Wi-SUN signals arrive at the GW. Additionally, the GW has a modulator and demodulator of LoRa and Wi-SUN, respectively, and the SIC function. Furthermore, the GW can exchange the accumulated signals among systems' modulator/demodulator. From the above, we evaluate packet error rate (PER) for LoRa received power-to-Wi-SUN received power ratio when these two signals interfere at the same time, as shown in Fig. 2.3.4.8. From Fig.2.3.4.8, it is confirmed that the PER of each signal is poor according to the increase of the received power radio because of capture effect when the GW does not execute the SIC algorism (c.f., black line). Meanwhile, with the SIC algorism, it is shown that the PER of each signal can achieve 0.0 [%] regardless of the receive power ratio (c.f., red line). This result is owing to spectrum spread of LoRa which the GW can demodulate the LoRa signals even if the received power ratio is less, besides the large received power ratio.

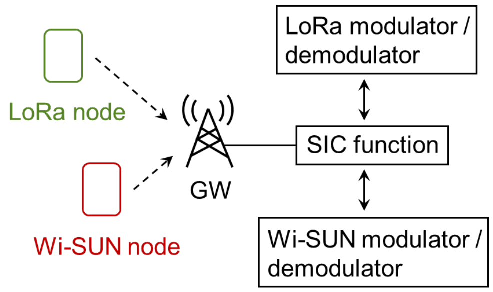


Fig. 2.3.4.7 Channel allocation based on the ECDF of the time occupancy of other systems.

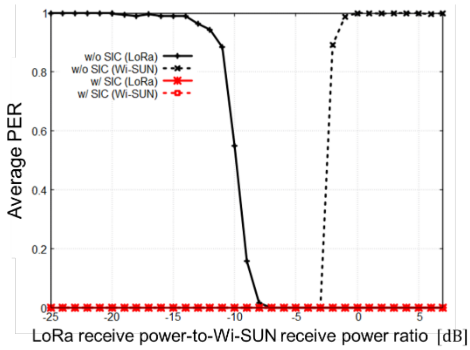


Fig. 2.3.4.8 Average PLR of LoRa nodes for the number of other system nodes.

[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 study proposes an adaptive CI exchange method when the occurred CI is biased.

Fig. 2.3.4.9 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 is decided by predicting 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. The ratio of transmission time per channel with conventional PLIM and with the proposed method are shown in Figs.2.3.4.10 and 2.3.4.11, respectively. Simulation results confirm that intensive selection of specific channels can be reduced.

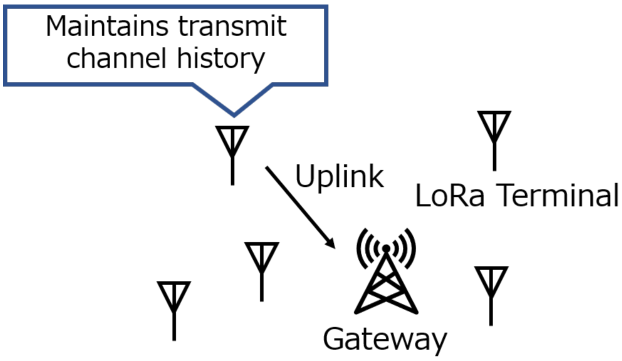


Fig. 2.3.4.10 System model

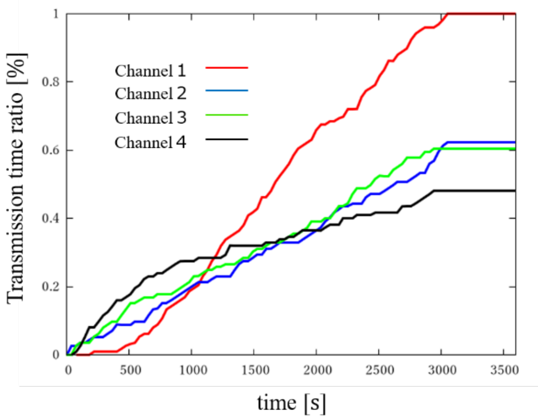


Fig. 2.4.3.10 Transmission time percentage transition of each channel with conventional PLIM.

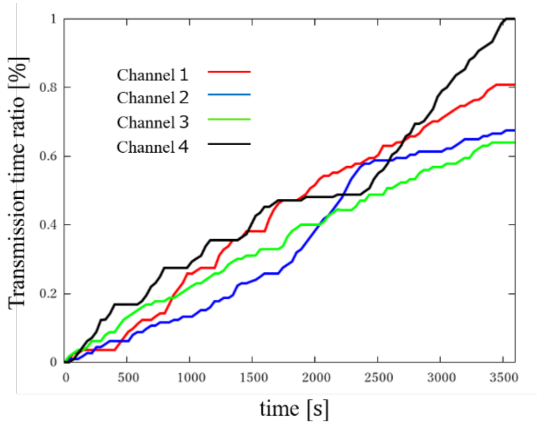


Fig. 2.3.4.11 Transmission time percentage transition of each channel with proposed method.

【Cooperative Research】

1. MIC SCOPE Phase I “Ultra Wide Area and Interference Tolerance Sub-GHz Wireless Sensor Network on Mixed Environment of Multiple Systems” Takeo Fujii

３．令和３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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【10】 上田康平, 令和 3 年度目黒会賞, 2022 年 3 月.（学部学生）

【11】 棚木拓海, 令和 3 年度目黒会賞, 2022 年 3 月.（学部学生）

【12】 安藤研吾, 令和 3 年度目黒会賞, 2022 年 3 月.（博士前期課程学生）

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特許

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