Mobile Communications Research Group
Tokyo Institute of Technology

2022

ANNUAL REPORT

Contents

Tokyo Institute of Technology

Overview

Tokyo Institute of Technology (Tokyo Tech) is the top national university for science and technology in Japan with a history spanning more than 130 years. Of the approximately 10,000 students at the Ookayama, Suzukakedai, and Tamachi campuses, half are in their bachelor's degree program while the other half are in master's and doctoral degree programs. International students number 1,200. There are 1,200 faculty and 600 administrative and technical staff members. In the 21st century, the role of science and technology universities has become increasingly important. Tokyo Tech continues to develop global leaders in the fields of science and technology, and contributes to the betterment of society through its research, focusing on solutions to global issues. The Institute's long-term goal is to become the world's leading science and technology university.

Mission

As one of Japan's top universities, Tokyo Tech seeks to contribute to civilization, peace and prosperity in the world, and aims at developing global human capabilities par excellence through pioneering research and education in science and technology, including industrial and social management. To achieve this mission, we have an eye on educating highly moral students to acquire not only scientific expertise but also expertise in the liberal arts, and a balanced knowledge of the social sciences and humanities, all while researching deeply from basics to practice with academic mastery. Through these activities, we wish to contribute to global sustainability of the natural world and the support of human life.

Main Building (Honkan) with "Sakura".

Tokyo Tech Seal

The Tokyo Tech seal was designed in 1947 by Mr. Shinji Hori, who was at that time a professor at the Tokyo Fine Arts School. The backdrop represents the Japanese character "工", which is the first character of "engineering, 工業". This part of the seal also evokes the image in silhouette of a window opening out on the world. Window is the second character of "school, 学窓". The central figure of the seal depicts a swallow and represents the Japanese character "大", which is the first character of "university, 大学". In Japan, swallows traditionally portend good fortune.
(Source: Tokyo Institute of Technology Profile, https://www.titech.ac.jp/english/about/)

Mobile Communication Research Group

Home page: https://www.mcrg.ee.titech.ac.jp

Mobile Communication Research Group (MCRG) of Tokyo Tech was established in 2001. The objective of the group is to conduct advanced research related to mobile communications. MCRG conducts comprehensive research on the development of mobile communication systems covering a wide range of cutting edge technologies in the field of the antenna design, wireless propagation, transmission systems, hard ware development, signal processing, and integrated circuit development.

MCRG Members

MCRG includes 5 core and 4 cooperate laboratories. Totally 8 professors, 5 associate professors, and 3 assistant professors belong to MCRG, in which Prof. Jun-ichi Takada is the principal researcher. The synergy in MCRG creates an ideal environment for cross-disciplinary discussions and tapping of expertise resulting in various notable joint projects and developments.

Core Laboratories

- Takada Laboratory (Propagation Lab.):
  Prof. Jun-ichi Takada, Assist. Prof. Hang Song
- Sakaguchi and Tran Laboratory (System Lab.):
  Prof. Kei Sakaguchi, Assoc. Prof. Gia Khanh Tran, and Emeritus Prof. Kiyomichi Araki
- Hirokawa Laboratory (Antenna Lab.):
  Prof. Jiro Hirokawa and Assist. Prof. Takashi Tomura
- Fukawa Laboratory (Signal Processing Lab.):
  Prof. Kazuhiko Fukawa and Assist. Prof. Yuyuan Chang
- Okada Laboratory / Shirane Laboratory (Device Lab.):
  Prof. Kenichi Okada and Assoc. Prof. Atsushi Shirane

Cooperate Laboratories

- Aoyagi Laboratory:
  Assoc. Prof. Takahiro Aoyagi
- Nishikata Laboratory:
  Assoc. Prof. Atsuhiro Nishikata
- Fujii and Omote Laboratory:
  Specially Appointed Prof. Teruya Fujii, and
  Specially Appointed Assoc. Prof. Hideki Omote
- Okumura Laboratory:
  Visiting Prof. Yukihiko Okumura

Activities

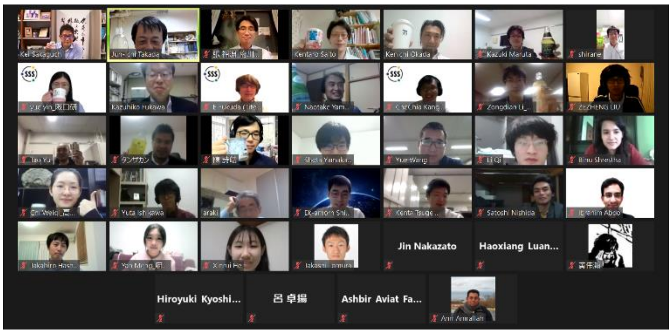
Beside the general research activities, for encouraging closer cooperation within MCRG and with the external companies, institutes and organizations, "Open House" and "Future Communication Research Workshop" are holed regularly. In addition, irregular invited speeches and lectures are also hold to broaden the horizons of MCRG members, especially the students.

Future Communication Research Workshop

An Future Communication Research Workshop (未来研究会) is organized every two months to share the latest research outcomes among internal laboratories and to gain insight on our research activities by the presentation and discussing in the seminar and poster section of each workshop.

Open House

From 2005, an Open House is organized yearly in April to introduce MCRG activities and build a network with external companies, institutes and organizations in the field of mobile communications. Distinguished speakers from both the academe and industry are invited to give key note speeches and lectures to contribute their visions and viewpoints for the future research and development of the mobile communications. From 2016, the Open House is organized in the collaboration with Advanced Wireless Communication Center (AWCC) of The University of Electro-Communications, and it brings on the further active research activities of both MCRG and AWCC.



Takada Laboratory

Home page: http://www.ap.ide.titech.ac.jp

Professor Jun-ichi Takada

Prof. Jun-ichi Takada was born in 1964, Tokyo, Japan. He received the B.E. and D.E. degree from Tokyo Institute of Technology in 1987 and 1992, respectively. He was a Research Associate at Chiba University during 1992-1994. He was an Associate Professor at Tokyo Institute of Technology in 1994-2006, and he has been a Professor since 2006. He is currently with the Department of Transdisciplinary Science and Engineering, School of Environment and Society. He is also serving as the Vice President for International Affairs, and the Director of the Institute of International Education. He was a part time researcher in National Institute of Information and Communications Technology from 2003 to 2007. His current research interests are the radio wave propagation and channel modeling for various wireless systems, applied radio measurements and information technology for regional/rural development. He is fellow of IEICE, senior member of IEEE, and member of Japan Society for International Development (JASID).

Assistant Professor Hang Song

Dr. Hang Song received the B.S. and M.S. degrees in electronic science and technology from Tianjin University, Tianjin, China, in 2012 and 2015, respectively. He received the Ph.D. degree from Hiroshima University, Hiroshima, Japan in 2018. From 2019 to 2020, he was a lecturer with the school of microelectronics, Tianjin University, China. From 2020 to 2022, he was a specially appointed researcher with the University of Tokyo, Japan. He is currently an assistant professor with Tokyo Institute of Technology. His research interests include wireless sensing, microwave and millimeter-wave imaging, wireless communication and networks, permittivity measurement, biomedical applications of microwave engineering. He is a member of IEICE and IEEE.

Postdoctoral Researcher Nopphon Keerativoranan

Dr. Nopphon Keerativoranan was born in 1989, Bangkok, Thailand. He received the B.E. degree (Hons.) from Thammasat University, Thailand, in 2012, the M.S. degree from Seoul National University, South Korea, in 2015, and the D.E. degree from the Tokyo Institute of Technology, Japan, in 2020. In 2012, he was a Telecommunication Engineer with Advance Info Service (AIS), Thailand. From 2015 to 2016, he was a Research Assistant with the National Electronics and Computer Technology Center (NECTEC), Thailand. His research interests include radio propagation channel modeling, RF-based motion sensing, radio channel modeling, and measurements for wireless communication system and application. He is a member of IEICE and IEEE.

Postdoctoral Researcher Sawaros Thanapornsangsuth

Dr. Sawaros (Sam) Thanapornsangsuth's research interests explore how education can be a foundational tool for sustainable development. Her goal is to study and promote a lifelong and innovative learning process that enables people to develop the knowledge, values, and skills. Driven by this goal, Dr. Thanapornsangsuth has extensive fieldwork experience in informal learning settings, both in the United States and abroad. Dr. Thanapornsangsuth was a tenure-track lecturer at the Department of Education Policy, Management and Leadership, Chulalongkorn University in Thailand. She graduated with a Doctor of Education degree from the Communication, Media, and Learning Technologies Design Program at Columbia University (USA).

Postdoctoral Researcher Xin Du

Dr. Xin Du was born in 1992, Harbin, China. He received the B.E., M.S., and D.E. degrees from the Tokyo Institute of Technology in 2017, 2019, and 2022, respectively. From 2017 to 2019, he was a Research Assistant in the School of Environment and Society, Tokyo Institute of Technology. His research interests include numerical electromagnetic simulation, diffraction theory, and reconfigurable intelligent surfaces. He is a member of the IEICE and IEEE.

Takada Laboratory has investigated radio propagation research to realize the next-generation wireless communication systems and the localization and sensing systems by the radio wave. The recent topics are the system-independent deterministic radio channel modeling for the development of wireless channel emulator of various cyber physical system. We also investigated the radio propagation model in underground railways system as well as the microstructure surfaces such as textile and non-planar serration. We are also developing the motion sensing technologies such as human breathing and human falling detection based on the radio propagation characteristics of the commercial wireless systems.

Another research topic is the establishment of radio propagation simulation techniques. The recent issues are the physical optics approach and the split-step parabolic wave equation. We also studied the environment model construction techniques from camera images and laser scanners for those propagation simulation researches.

Recently, the passive reflectors and reconfigurable intelligent surfaces for illumination of shadowed regions is being developed for robust millimeter wave mobile communication systems. Measurement and modeling of dynamic radio channel at Terahertz band is also being investigated for 6G communication systems. Besides, the techniques of imaging and permittivity measurement with millimeter-wave radar are being developed.

In addition, we are also involved in the ICT research for sustainable development. The individual topics are addressed as follows.

Takada Laboratory

Recent Research Topics

- **Radio Propagation Simulation and Channel Modeling Research**
  - Simplified Knife-Edge Diffraction Model for Vehicle Shadowing
  - Grid-based Channel Emulation Technique with Additional Obstacle
  - Synchronized Dynamic Channel Sounder and Posture Capture for Millimeter Wave Radio Channel Affected by Human Body Shadowing
  - Design of Parameters of Fast Fourier Transform for Three-dimensional Split Step Parabolic Equations and multi-planes Kirchhoff Approximation
  - Study on Propagation Prediction in Non-Planar Serration Object at Millimeter-Wave Band Utilizing Physical Optics

- **Applications of Radio Wave for Detection, Sensing, and Measurement**
  - Optical Measurement of Tissue Conductivity in Microwave Range with Cell-level Resolution
  - Complex Permittivity Measurement Using mmWave Frequency Modulated Continuous Wave (FMCW) Radar
  - Indoor Multi-Person Detection Utilizing Breathing-Induced Wi-Fi Channel State Information
  - Human Detectability of the Backscattering mmWave Signal from Through-Glass Propagations

- **ICT for development, education for sustainable development**
  - Enhancing ICH Safeguarding and Transmission using ICT in Luang Prabang

Simplified Knife-Edge Diffraction Model for Vehicle Shadowing

(Supported by the Ministry of Internal Affairs and Communications)

Vehicle shadowing poses a significant problem to the low-profile mobile communication. The simplified knife-edge diffraction (KED) model is developed to estimate the shadowing by a cuboid object in near real-time. The model is validated by using a full-wave electromagnetic simulation of a vehicle body object. Moreover, the effect of vehicle shape is investigated by comparing the simulation of vehicle body to that of cuboid. The simulation scenario is shown in Fig. 1.

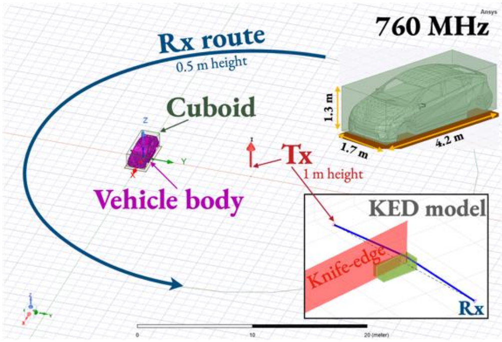


Fig. 1. Simulation scenario

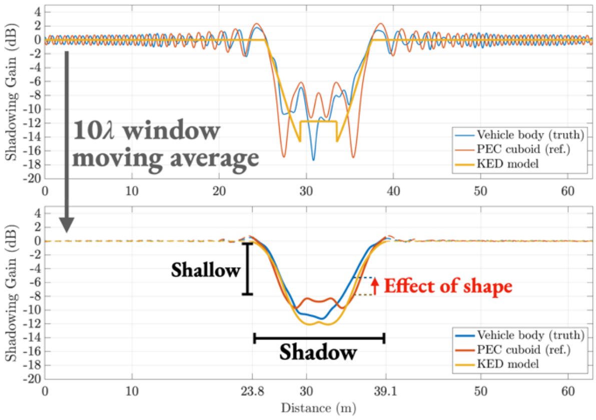


Fig. 2. Validation result

The cuboid and vehicle body obstacles are shown in the upper right, and the developed KED model is shown in the bottom right. At 760 MHz, the shadowing gain simulated from the KED model, vehicle body, and cuboid is presented in Fig. 2. Shadowing component is extracted by applying 10λ window moving average along Rx route. The result shows good agreement in the shallow shadow region which is more important to the communication system than the deep shadow. The effect of shape is found to be due to the sloped front.

Grid-based Channel Emulation Technique with Additional Obstacle

(Supported by the Ministry of Internal Affairs and Communications)

Grid-based channel emulation technique was introduced to realize wireless channel emulator with accurate drive-testing of wireless communication. The emulation technique pre-computed deterministic path parameters at each grid node and stored in the database. Then, the channel response of user terminal (UE) at a particular position is emulated based on the interpolated path parameters from neighboring grid nodes. In this year, the technique is extended to handle the presence of additional obstacles introduced by the emulator. A simplified knife edge diffraction model is applied to calculate the diffraction gain due to cuboid shadowing which is contributed to the path weight at each grid node. The same interpolation procedure is used to emulate the UE channel. Simulation was designed to validate the modified interpolation technique with a cuboid which was assumed to obstruct the propagation between the reflected path from the wall and the UE. Two cuboids with different cross-section sizes (0.4 and 1 m) were used for comparison while the grid size was fixed at 1 m. the modified interpolation scheme overestimates the diffraction gain the most at the shadowing depth. Additionally, the larger the object relative to the grid size is, the smaller the discrepancy becomes as indicated in Fig. 1.

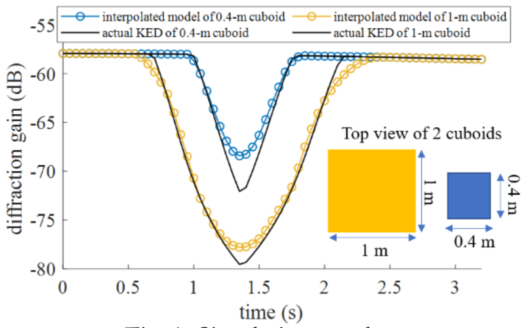


Fig. 1. Simulation result

Takada Laboratory

Synchronized Dynamic Channel Sounder and Posture Capture for Millimeter Wave Radio Channel Affected by Human Body Shadowing

(Supported by the National Institute of Information and Communications Technology 02701)

Base stations at millimeter wave band point the main beam to the line-of-sight (LoS) toward the mobile stations. However, communication relying on only LoS channel suffers from a deep fading due to human blockage. In this work, a synchronized measurement system including dynamic channel sounding and motion capture has been developed to predict the impact due to human blockage. We synchronize the 2 different devices by feeding an external trigger signal as the time reference. For validation, the measurement of dynamic channel and motion capture, and the uniform theory of diffraction for an elliptic cylinder model were done. The results show that the proposal matches the time stamps well. The proposal provides a reliable synchronization of channel sounder and motion capture for developing the model of the dynamic radio channel affected by human shadowing.

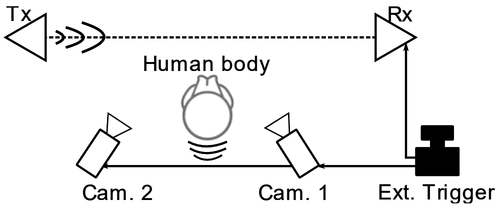


Fig. 1. Hardware architecture

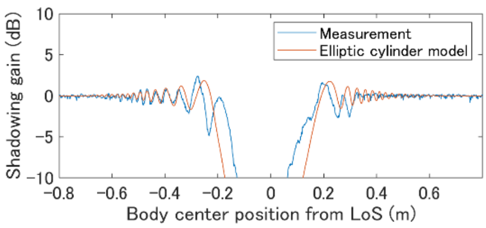


Fig. 2. Elliptic cylinder approximation

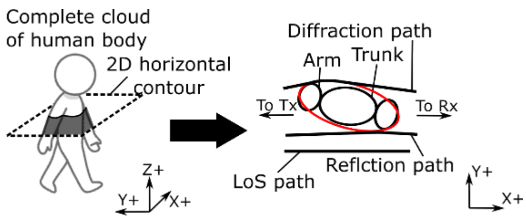


Fig. 3. Elliptic cylinder approximation

Design of Parameters of Fast Fourier Transform for Three-dimensional Split Step Parabolic Equations and multi-planes Kirchhoff Approximation

(Supported by the National Institute of Information and Communications Technology 02701)

The prediction of the shadowing effect by a human blockage in the lit region is important to maintain a stable mobile communication for the beyond fifth generation (B5G) systems. As the fast prediction techniques, the split step parabolic equations (SSPE) and multi-planes Kirchhoff approximation (KA) have been widely used. This work designs the parameters of a fast Fourier transform (FFT) for three-dimensional SSPE and MKA. The size of FFT and the 3D windowing functions are proposed. The proposal is validated for the perfect electric conductor (PEC) and human-skin spheres in the lit region at terahertz (THz) band with the different polarization (V/H), by the exact solutions of the PEC and dielectric spheres. As shown in Fig. 1, the proposal shows a good agreement with the exact solutions.

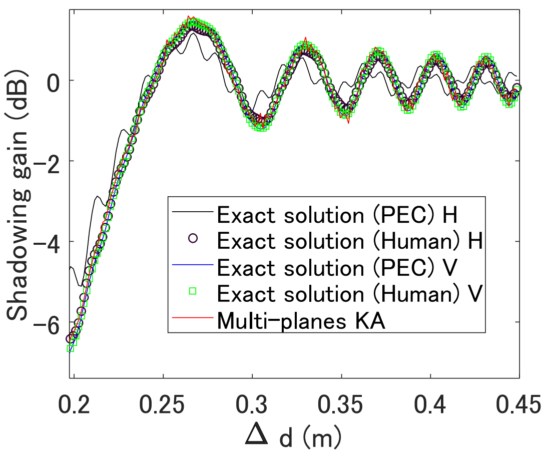


Fig. 1. Shadowing gain in lit region

Optical Measurement of Tissue Conductivity in Microwave Range with Cell-Level Resolution

(Supported by JSPS KAKENHI 22K14299)

Microwave has been widely studied for biomedical applications such as imaging and treatment. When the microwave propagates into the tissues, absorption will occur and the electromagnetic energy is converted into heat. The accurate knowledge of conductivity is critical to develop non-invasive technologies. Furthermore, conductivity is also vital for dosimetry studies which help determine microwave safety thresholds.

Therefore, the knowledge of conductivity of tissues within microwave range is essential to promote the development of imaging technologies, as well as facilitate the investigation of the safety thresholds. Current dielectric measurement methods such as open-coaxial probe can only give the bulk average property in the sensing region. The conductivity with single cell resolution is not achievable yet. In this project, an innovative optical measurement technology will be developed for characterizing the conductivity of tissues at cell level. Measurement system and protocols will be developed to challenge the precise conductivity measurement of tissues at single-cell resolution, which is expected to differentiate the characteristics of different cells in tissues. With the developed technology, the conductivity information of different tissues in micrometer-scale resolution can be revealed, which is promising to significantly contribute and facilitate the research field of microwave biomedical engineering.

Complex Permittivity Measurement Using mmWave Frequency Modulated Continuous Wave (FMCW) Radar

Permittivity measurement can be used for many applications such as quality inspection, component analysis, etc. In conventional measurement methods, vector network analyzer (VNA) is basically required. In order to achieve portability and easy accessibility, a technique for measuring material dielectric property utilizing mmWave FMCW radar is proposed in this research. The measurement system mainly consists of the stage, radar module, and the indicator as shown in Fig. 1. The position of radar and the material under test (MUT) can be adjusted precisely with the stage and indicator. In the measurement, the metal plate is utilized for calibration and then the measurements are conducted several times when the distance difference between metal and MUT is from 0 mm to 1 mm. Acrylic plate was used to test the performance. The results are shown in Fig. 2. After fitting, the complex permittivity was 2.47-0.03j, which shows good agreement with other work.

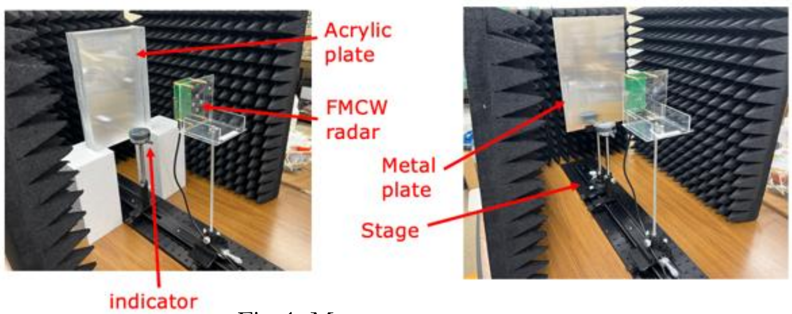


Fig. 1. Measurement system

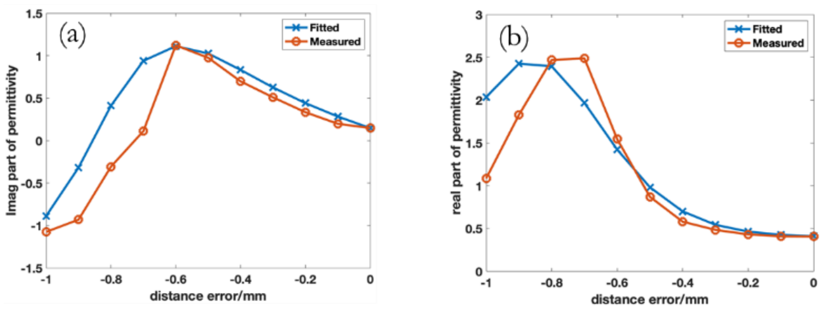


Fig. 2. Measurement result and fitted result.
(a) real part; (b) imaginary part

Takada Laboratory

Study on Propagation Prediction in Non-Planar Serration Object at Millimeter-Wave Band Utilizing Physical Optics

The propagation characteristics in urban and indoors have been widely predicted by using ray tracing (RT) simulation. The unform theory of diffraction (UTD) and geometrical optics (GO), both of which assume that waves are rays, are the basis of RT. GO predicts the specular reflection (SC) on an infinite surface area while UTD predicts the diffraction for a semi-infinite half-plane. Unfortunately, a planar scatterer might not be able to approximate the RT calculation for the surface irregularity, and it cannot be negligible at higher frequencies. In contrast, the physical optics (PO) approximation uses the equivalent current of the object to calculate the scattered field on the illuminated surface. The advantage of PO allows for the observation of the scattered field's mechanism on the non-planar surface. As shown in Fig. 1, the serration periodic structure with the dimension of 73.8 cm × 97 cm is used to compute the scattered wave. Hence, scattering characteristics at a serration, which is a typical building facade material with a rough surface, are investigated by comparing PO and RT.

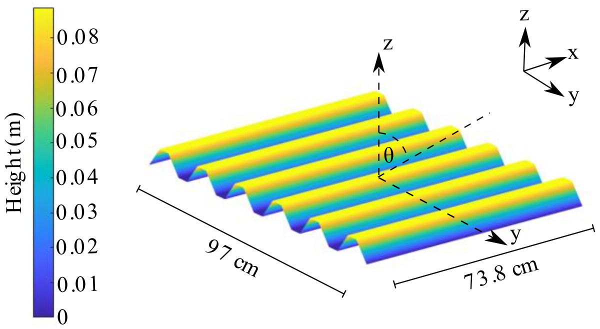


Fig. 1. Dimension of the serration periodic structure

Indoor Multi-Person Detection Utilizing Breathing-Induced Wi-Fi Channel State Information

Device-free detection has gained attention for emerging applications, and many recent techniques are based on Channel State Information (CSI) which can be extracted from Wi-Fi infrastructure. However, the presence of multiple people challenges the multipath resolvability of the narrow-bandwidth Wi-Fi system. Thus, this study aims to observe the feasibility of indoor multiple-person detection from breathing-induced CSI, by considering various factors, including positions, body alignment, signal-to-noise ratio (SNR), and time window.

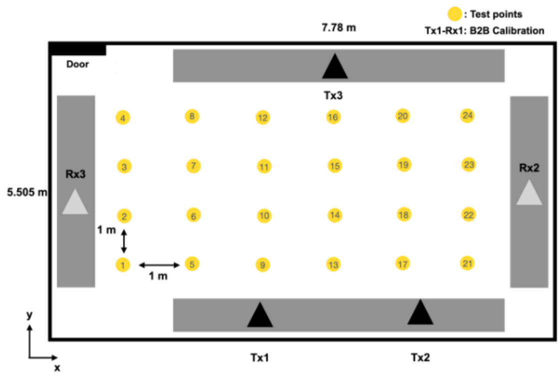


Fig. 1. Indoor simulation scenario

Two subjects are located in the simulation scenario shown in Fig. 1. Regarding the geometrical optics concept, each person is assumed to be a point on a plane that moves with a breathing pattern. Then, CSI is derived, the distance range profile is estimated and further used to determine detectability from the correct number of peaks detected. By comparing the plot of detectable probability over propagation path length difference of the default setup (20 dB SNR, 20 s time window, and +x facing direction) with the varied setups, all four parameters are found to affect the detectable trend as shown in Fig. 2. However, the proposed simulation model has a limitation to represent the actual scenario due to the simplification of the human subject.

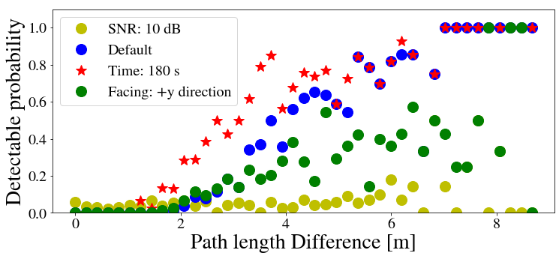


Fig. 2. Detectable probability VS path length difference in the varied parameter setup

Human Detectability of the Backscattering mmWave Signal from Through-Glass Propagations

(Supported by IEEE Antenna and Propagation Society)

Millimeter radars for human body and gesture detection are in development stages and have potential to be applied to electronic devices in the future. Being put under the glass protective layers and of these devices, it is needed to research how glasses affect the detection performance. This research aimed to investigate the power of backscattered millimeter waves from a human body through a glass plate emitted from a radar in order to find how the glass affects the power of the detection at different incident angles.

Multiple measurements were conducted to measure the power of backscattered waves from the human body and a wave reflector through a glass plate, and without the plate. The result is then post-processed to counteract the effects of surrounding environments on the experiment. Finally, a backscattered wave pattern from human body through the glass could be achieved as in Fig. 1. It could be seen that the power of this wave is stronger near 0 degree and quickly decreases as the incident angle increases. Overall, this research found that the backscattered wave power was reduced by the existence of the glass layer, and this reduction effect increased at higher incident angle of the wave following a similar pattern predicted from theory.

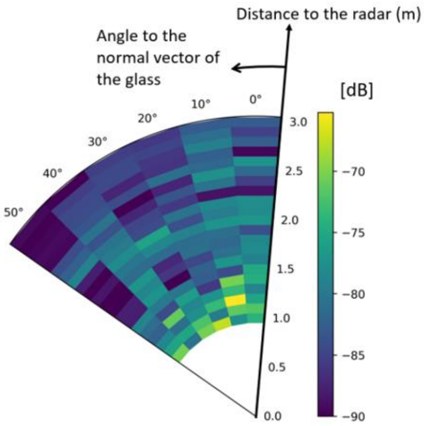


Fig. 1. Power of backscattered wave through the glass by human position

Enhancing ICH Safeguarding and Transmission using ICT in Luang Prabang

(Supported by Grant for Global Sustainability)

This project aims to enhance the safeguarding of intangible cultural heritage (ICH) in the Town of Luang Prabang World Heritage Site in Lao PDR using information and communications technology (ICT). The objectives are: 1) to promote Luang Prabang's ICH by developing an ICH database and 2) to facilitate youth's active engagement in the ICH safeguarding process using digital technology.

Activity 1: Database development for archiving digital ICH information

A fieldwork was conducted in Luang Prabang from May to June 2022 to measure both the baseline ICH awareness and digital profile of the local community through a quantitative survey. Moreover, a two-month website development online training among the ICT Section of DPL was successfully conducted. An operational ICH database was co-developed with the DPL during the training. It serves as an ICH knowledge repository that can be accessed online by local community through a digital device.

Activity 2: Facilitation of youth's active engagement in ICH transmission and safeguarding

The "Luang Prabang Youth Ambassadors' Forum" was organized along with 25 youth ambassadors (14 male, 11 female) from July – October 2022. The youth Ambassadors received training on cultural heritage knowledge, ICH safeguarding approaches and their linkages with SDGs. Additionally, the youth ambassadors were introduced to the design thinking process as a tool for them to create innovative solutions to ICH challenges. Finally, the Presentation Showcase Day provided a venue for the youth ambassadors to present and share their project ideas and digital stories of community-level ICH.

Professor Kei Sakaguchi

Prof. Kei Sakaguchi received the M.E. degree in Information Processing from Tokyo Institute Technology in 1998, and the Ph.D degree in Electrical & Electronics Engineering from Tokyo Institute Technology in 2006. Currently, he is working at Tokyo Institute of Technology in Japan as a Dean in Tokyo Tech Academy for Super Smart Society and as a Professor in School of Engineering. At the same time, he is working for oRo, Co.,Ltd. in Japan as an outside director. He received the Outstanding Paper Awards from SDR Forum and IEICE in 2004 and 2005 respectively, and three Best Paper Awards from IEICE communication society in 2012, 2013, and 2015. He also received the Tutorial Paper Award from IEICE communication society in 2006. His current research interests are in 5G cellular networks, millimeter-wave communications, wireless energy transmission, V2X for automated driving, and super smart society. He is a fellow of IEICE, and a member of IEEE.

Associate Professor Gia Khanh Tran

Assoc. Prof. Gia Khanh Tran was born in Hanoi, Vietnam, on February 18, 1982. He received the B.E., M.E. and D.E. degrees in electrical and electronic engineering from Tokyo Institute of Technology, Japan, in 2006, 2008 and 2010 respectively. He became a faculty member of the Department of Electrical and Electronic Engineering, Tokyo Institute of Technology since 2012, and now he is working as Associate Professor. He received IEEE VTS Japan 2006 Young Researcher's Encouragement Award from IEEE VTS Japan Chapter in 2006 and the Best Paper Awards in Software Radio from IEICE SR technical committee in 2009 and 2012. His research interests are MIMO transmission algorithms, multiuser MIMO, MIMO mesh network, wireless power transmission, cooperative cellular networks, sensor networks, digital predistortion RF and mm-waves. He is a member of IEEE and IEICE.

Emeritus Professor Kiyomichi Araki

Emeritus Prof. Kiyomichi Araki was born in 1949. He received the B.S. degree in electrical engineering from Saitama University, in 1971, and the M.S. and Ph.D. degrees in physical electronics both from Tokyo Institute of Technology in 1973 and 1978 respectively. In 1973-1975, and 1978-1985, he was a Research Associate at Tokyo Institute of Technology, and in 1985-1995 he was an Associate Professor at Saitama University. In 1979-1980 and 1993-1994 he was a visiting research scholar at University of Texas, Austin and University of Illinois, Urbana, respectively. From 1995 to 2014 he was a Professor at Tokyo Institute of Technology. His research interests are in information security, coding theory, communication theory, ferrite devices, RF circuit theory, electromagnetic theory, software defined radio, array signal processing, UWB technologies, wireless channel modeling and so on. Prof. Araki is a member of IEEE, IEE of Japan, Information Society of Japan and fellow of IEICE.

S.A. Associate Professor Tao YU

S.A. Assoc. Prof. Tao Yu received his M.E. degree from the Communication University of China (CUC), Beijing, China in 2010, and the Dr.Eng. degree from the Tokyo Institute of Technology (Tokyo Tech), Tokyo, Japan in 2017. From 2014 to 2015, he was a visiting student in Osaka University. From 2017 to 2022, he worked as a postdoctoral researcher in Sakaguchi Lab, Dept. Electr. Electron. Eng., Tokyo Tech. From 2022, he joined the Tokyo Tech Academy for Super Smart Society where he is working as a specially appointed associate professor. His research interests include UAV communication, V2X, sensor networks, localization, antenna, smart mobility, and building energy management. He is member of IEEE and IEICE.

Sakaguchi-Tran Laboratory

Tokyo Tech mmWave Beyond 5G Cellular Networks

MmWave coverage expansion by Repeaters

The introduction of the millimeter wave (mmWave) band with 5G has led to remarkable improvements in the speed and capacity of mobile communication systems, also known as eMBB (enhanced Mobile Broadband). However, mmWave has high propagation loss and straightness, making it difficult to ensure coverage. In the Ookayama Beyond 5G (B5G) demonstration field constructed by our laboratory, we encountered a challenge in achieving high millimeter wave throughput over a large area. To address this issue, we conducted a study on a millimeter wave analog repeater, which consisted of a donor unit with beamforming capability and a service unit equipped with amplification and re-radiation capacity. Our goal was to investigate the repeater's potential to improve communication quality in the deployed mmWave area. We introduced the repeater to the area and evaluated its performance, and our results showed that the communication quality significantly improved at most receiving points, demonstrating the potential of mmWave technology.

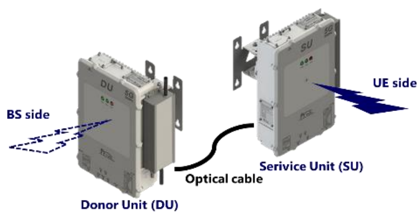


Fig. 1 MmWare Analog Repeater

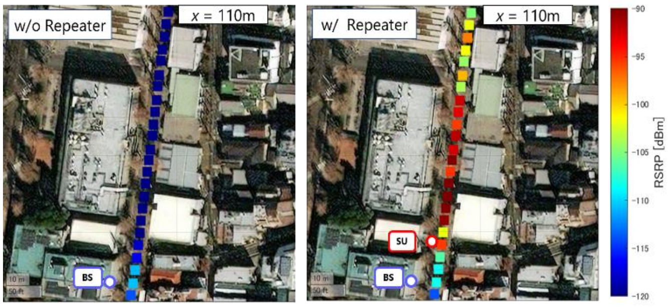


Fig. 2 Expansion of MmWare Area by Repeaters

Digital Twin Platform for mmWave Propagation Analysis toward 6G

We are currently developing a digital twin platform capable of replicating the wireless propagation environment in cyberspace. In this cyberspace, information regarding physical base stations and relay stations can be recreated based on both actual measurements and simulations, with the ability to feed this information back to the physical space. As part of this platform, we have designed and implemented a web-based map plotting application and an onsite AR visualization tool. Our proposed system facilitates efficient construction and implementation of mmWave coverage areas.

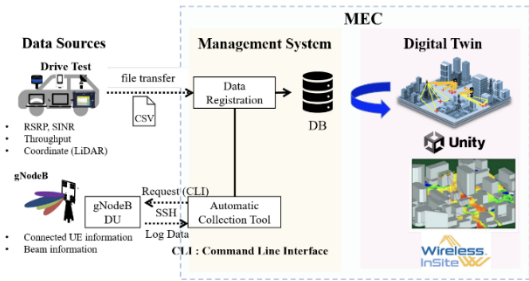


Fig. 3 Concept of Digital Twin Platform

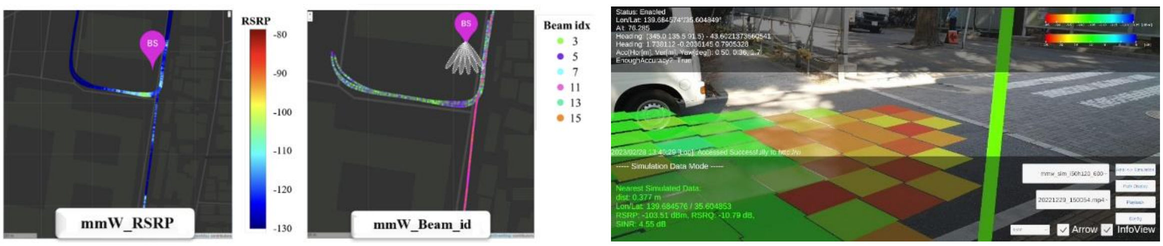


Fig. 4 Examples of Digital twin-based Visualization

Massive MIMO

Introduction

Massive MIMO (Multiple-Input Multiple-Output) is a technology that uses a large number of antennas at the base station to improve the capacity and efficiency of wireless communication systems. The technology has gained a lot of attention in recent years due to its ability to provide significant improvements in the performance of wireless networks. Massive MIMO is expected to play a significant role in the development of 5G and beyond 5G, enabling faster data rates, improved coverage, and enhanced reliability. The application scenario includes smart cities, autonomous vehicles, and the Internet of Things (IoT).

Multi-user mmWave Massive Relay MIMO System

This system used a large number of relay stations to generate artificial channels and construct an analog massive relay MIMO. Therefore, it can expand the coverage of one station, and based on this system, MIMO transmission was enabled, which was difficult to achieve in mmWare, and the channel capacity was significantly improved. In addition, the massive RSs can increase system reliability by choosing to use different relay stations. We have expanded the original single user into a multi-user system as Fig. 5 and optimized the allocation of RSs and beams for users to increase the system channel capacity.

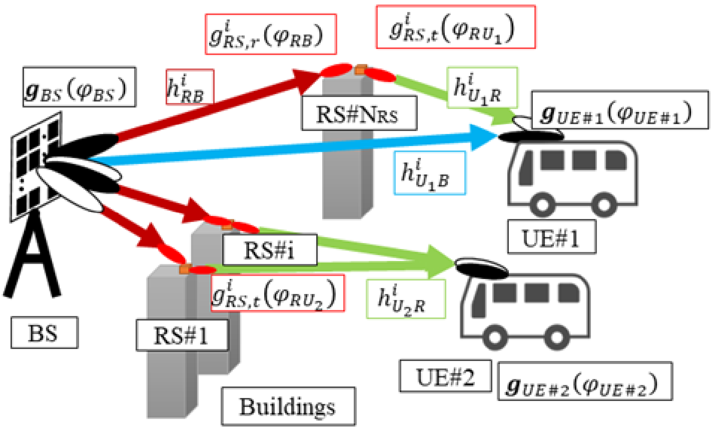


Fig. 5 Massive Relay MU-MIMO System

In the linear simulation environment as in Fig. 6, all the relay stations were installed on the roof of the building. One user is in a fixed position and another user is moving along the line. We proposed to use the block disorganization precoding method to reduce the interference between different users and resource block allocation to increase the utilization of the system resource especially when the distance of users is short. As a result, a notable improvement in channel capacity can be seen in Fig. 7.

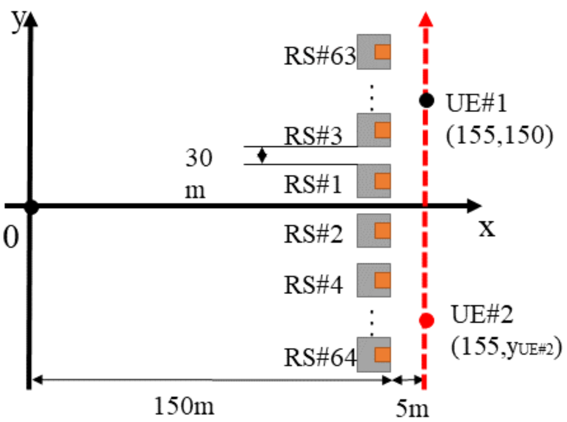


Fig. 6 Simulation Environment

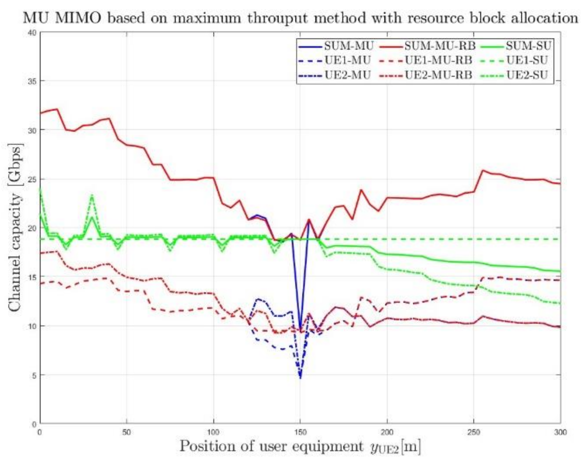


Fig. 7 Simulation Result

Sakaguchi-Tran Laboratory

Smart mobility Digital Twin Platform

Smart mobility R&E Field in Tokyo Tech

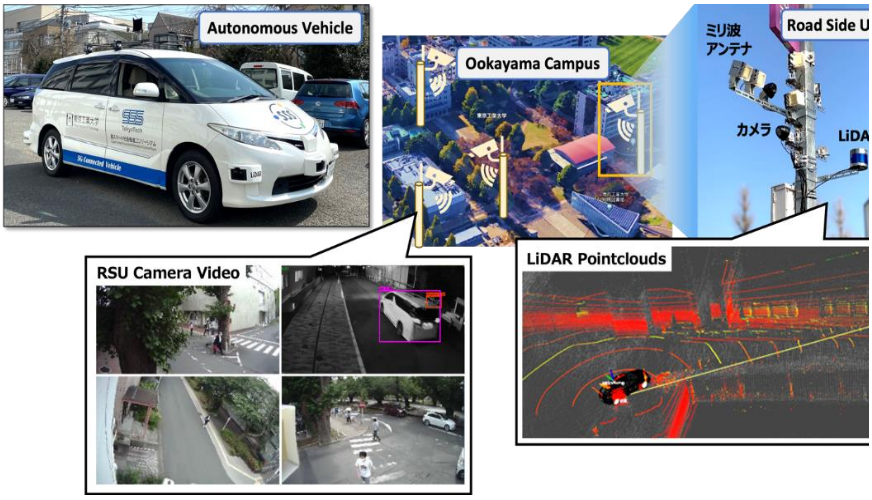


Fig. 8 Facilities of Smart Mobility R&E Field

Sakaguchi-Tran Lab is committed to exploring new research and developing new technologies to support smart mobility services. The Smart Mobility R&E Field is a full-fledged and world-leading platform for autonomous driving and V2X (vehicle-to-Everything) related research. Advanced wireless infrastructures (LTE/5G NR/DSRC/WiGig) and costly equipment (Robocar/LiDAR/HD camera) are freely accessible.

Our recent outcomes upon this platform include an application of blind-spot vision for safe driving using AR glasses, image size reduction by edge processing for low-latency relay transmission, and multi-camera networks using millimeter-wave backhaul. Notably, this R&E field has boosted extensive collaborative research with industrial partners such as Fujitsu, DENSO, Panasonic, and Map IV. More information is delivered by this video: https://youtu.be/dgABLFsirw0.

Digital Twin Platform for Smart Mobility Planning

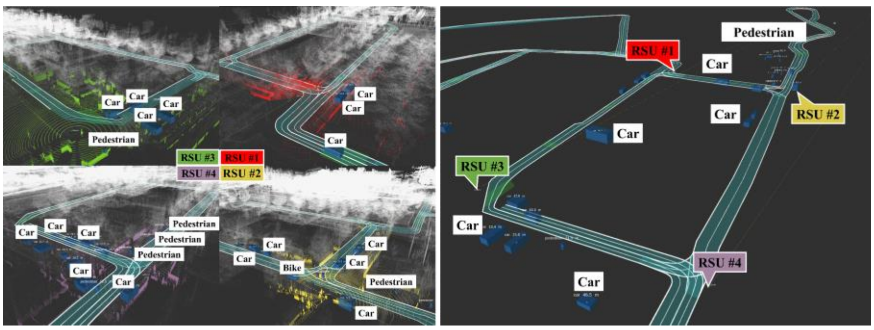


Fig. 9 RSU Edges and Cloud Environment Perception

Based on the Smart Mobility R&E Field, Sakaguchi-Tran Lab focuses on the modeling of a real-time digital twin platform to realize automated driving with good safety and high commuting efficiency by utilizing cloud and edge computing. In our design, the real-time digital twin model integrates and visualizes static objects (e.g., buildings, infrastructures, and roads) and dynamic objects of interest (e.g., traffic participants including vehicles and pedestrians); Then a smart mobility digital twin platform is proposed to serve connected automated vehicles functionally based on cooperative perception and V2X communications; We also exploit the cloud/edge communication and computing capabilities by allocating different functions and services over the cloud and the edge planes (environment perception at RSU and OBU edges, cooperative perception and route planning in the cloud, and motion planning as well as motion control in the vehicle edges). Finally, we implement the proposed platform to monitor real traffic and provide services for automated vehicles, then study and evaluate its performance from the standpoints of functionality and latency.

Digital Twin-Enabled Applications

Based on the developed digital twin platform, we focused on the car-sharing system and intelligent traffic system (ITS) to provide services to connected and automated vehicles (CAVs). In the study of car-sharing, we propose an optimal delivery system for automated vehicles with the assistance of the digital twin. In particular, we deal with the car-sharing system as a use case of smart mobility platforms. We implement our system by utilizing V2X-enabled digital twin to analyze and feedback optimized delivery plans to automated vehicles. The simulation and actual experiment results confirmed that the proposed car-sharing system can effectively reduce overall delivery time by 63%. Significantly, we found a negligible gap between the simulation and the experiment using the digital twin.

For ITS, we propose a solution using dynamic scheduling, which calculates the timing for each car to pass through an intersection in real-time. In addition, we aim to eliminate potential hazards by not only using RSUs to supplement vehicle blind spot information but also by using object recognition information based on RSU sensors to predict vehicle and human movement.

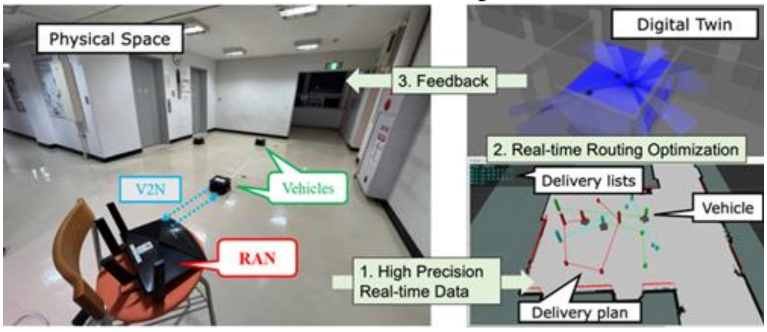


Fig. 10 In-door Car-sharing System

Fig. 11 Digital Twin for ITS

Design and Development of a Disaster Rescue Support Multi-UAV System Operating at 5.7GHz Band

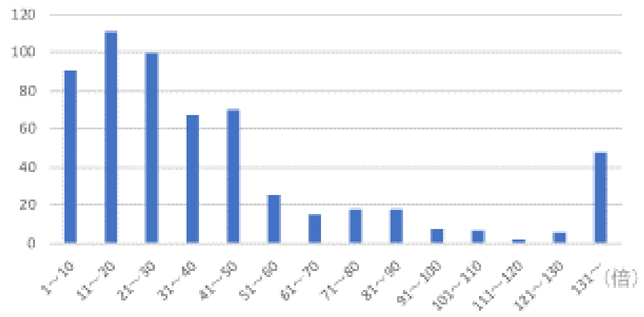


Fig. 12 Percentage Improvement in Search Time When 9 Units are Used

In recent years, the drone industry is expected to see ever-increasing demand, and it is estimated that drones will be used in a wide variety of cases, including disasters, logistics, agriculture, and security. Among these, rescue support systems are urgently needed in Japan, where there are many disasters and accidents. Currently, many organizations are beginning to seriously consider implementing rescue support systems using UAVs. In our study, we describe a real-time, high-capacity communication system with directional antennas mounted on a drone that enables real-time communication over long distances. By upgrading the subsystems based on this communication system, we aimed to design and develop a next-generation UAV rescue support system that significantly improves the search range and search time compared to the current system, and also improves reliability by using multiple data. The result was a 33.8-fold increase in search speed and a 25-fold increase in area coverage over the previous system, with reliability approaching 100%.

Performance Analysis on the Construction of MmWave-based IAB-UAV Networks

UAVs have attracted attention from a wide range of industrial applications, including logistics, infrastructure inspection, agriculture, and security. In the field of communications, research is underway to form temporary networks from the air by using UAVs as base stations. UAV base stations provide communications to users in the event of a disaster by replacing failed ground base stations.

To deploy millimeter-wave base stations at higher density, the 3GPP (3rd Generation Partnership Project) is standardizing IAB (Integrated access and backhaul) technology, which integrates wireless access and wireless backhaul in the same frequency band. As shown in Fig. 13, the backhaul and communication to UE aren't scheduled at the same timings. We reported the throughput and limitation of the hop number of our proposed IAB-UAV networks. And we evaluated the coverage of it as shown in Fig. 14.

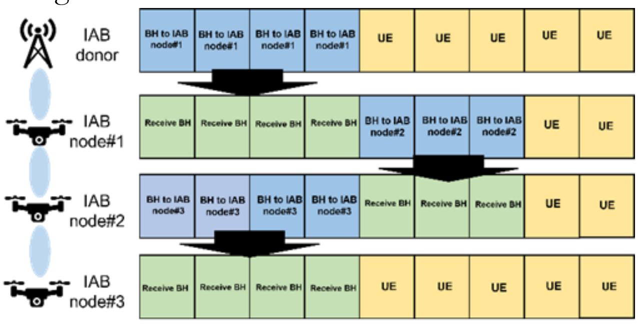


Fig. 13 The scheduling method of IAB

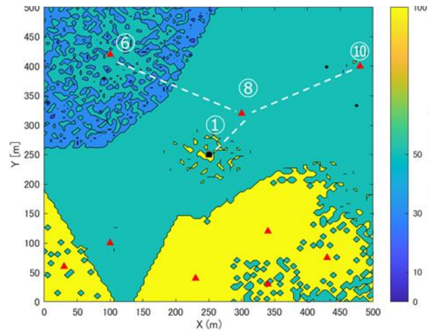


Fig. 14 The coverage with 10 UAVs

AI-based Radio Resource Management for UAV Wireless Networks

Over the past few years, with the rapid increase in natural disasters, the need to provide smart emergency wireless communication services becomes crucial. The first few hours after a catastrophe are regarded as the "golden hours" of relief because rescue workers have a high probability of evacuating people from the damaged region during this period. As a result, it is critical to developing an emergency wireless network that is completely independent of the conventional broadband network as soon as possible to preserve those valuable human lives. Unmanned Aerial Vehicles (UAVs) got high attraction as promising candidates due to their unprecedented capabilities and broad flexibility.

Notwithstanding the advantages of utilizing UAVs to establish emergency wireless communication networks in the post-disaster area, there are a bunch of issues that need to be neutralized. Firstly, in this tough environment induced by a natural disaster, the UAV should design and optimize its flying route. Secondly, the available energy for victims is ephemeral due to the limited battery capacity of their UEs and the destruction of the power supply infrastructure as a result of the natural disaster. Thirdly, the UAV's operating duration is restricted by the attached onboard battery's capacity. The UAV should return to its base for recharging when it is almost completely depleted. Therefore, while constructing an emergency wireless communication network, all these concerns should be addressed. In addition, since this is a crucial mission, the UAV must assist as many people as possible in the disaster zone before its battery dies. Consequently, seeking a robust mathematical tool capable of tackling such novel challenges becomes vital. Our research utilizes reinforcement learning (RL) algorithms, precisely speaking multi-armed bandit (MAB) algorithms to tackle such an unprecedented optimization problem.

UAV-based Localization Networks

Localization of radio emitter is used for mobile device services and radio monitoring. Geometric localization using ground-based sensors has a problem of estimation accuracy degradation in environments where the source and sensor are out of sight (NLoS). In this research, a UAV is used as a sensor to ensure line-of-sight (LoS) and enable low-cost, high-accuracy localization.

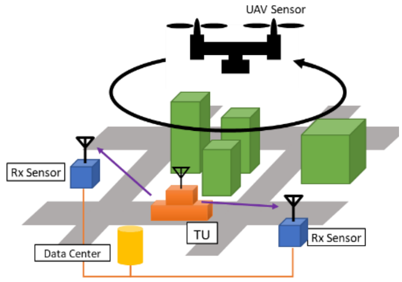


Fig. 15 Localization Using UAV Senser

The statistical position estimation method, position fingerprinting, extended to the time axis and introduced machine learning, can be used for highly accurate position estimation. This is demonstrated by simulations and experiments using line tracers. Also, optimization of the UAV's flight path using PSO improved the position estimation error by about 93% compared to that of fixed sensors.

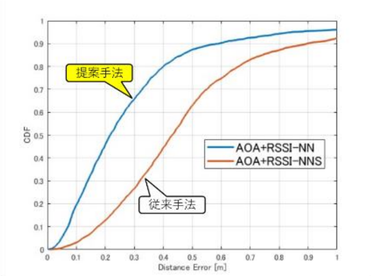


Fig. 16 Localization with Neural Networks

Fig. 17 Experiments Using Line Tracers

Antenna System Design for WLAN

With the spread of PCs and smartphones in recent years, there has been a growing demand for MU-MIMO technology which is suitable for wireless communication by multiple people in places such as offices and classrooms. However, when implementing MU-MIMO in an indoor environment, there is not much knowledge of where to install the AP and how to configure the antenna. The research object is to design the antenna arrangement on the AP side of the MU-MIMO system in an indoor environment and obtain an antenna arrangement plan that provides excellent system capacity by data analysis. Using a lecture room at Tokyo Tech's Okayama Campus as a model, a transmitting antenna is installed on the ceiling, and the communication capacity of the receiver is calculated using SVD-MIMO as the coding method. Simulate the MIMO antenna on the receiving side with different placement patterns to find a layout that provides excellent distribution of communication characteristics. Furthermore, genetic algorithms change the parameters of the placement pattern within a range to search for the best layout. Research result shows that in the arrangement pattern, the best layout was obtained when d1 = d2 = 1m, as shown in Fig. 18.

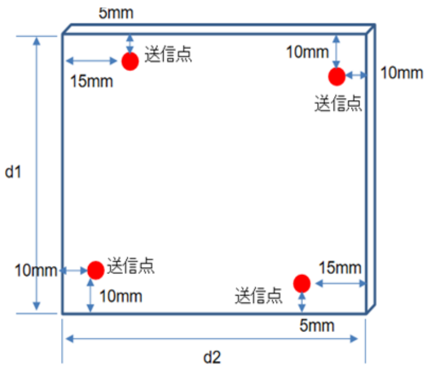


Fig. 18 The Best Layout

Hirokawa Laboratory

Home page: http://www-antenna.ee.titech.ac.jp

Professor Jiro Hirokawa

received the B.S., M.S. and D.E. degrees in electrical and electronic engineering from Tokyo Institute of Technology (Tokyo Tech), Tokyo, Japan in 1988, 1990 and 1994, respectively. He was a Research Associate from 1990 to 1996 and an Associate Professor from 1996 to 2015 at Tokyo Tech. He is currently a Professor there. He was with the antenna group of Chalmers University of Technology, Gothenburg, Sweden, as a Postdoctoral Fellow from 1994 to 1995. His research area has been in slotted waveguide array antennas and millimeter-wave antennas.

He received IEEE AP-S Tokyo Chapter Young Engineer Award in 1991, Young Engineer Award from IEICE in 1996, Tokyo Tech Award for Challenging Research in 2003, Young Scientists' Prize from the Minister of Education, Cultures, Sports, Science and Technology in Japan in 2005, Best Paper Award in 2007 and a Best Letter Award in 2009 from IEICE Communications Society, and IEICE Best Paper Award in 2016 and 2018. He is a Fellow of IEEE and IEICE.

Assistant Professor Takashi Tomura

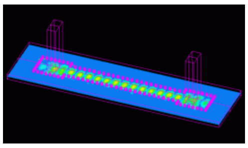
received the B.S., M.S. and D.E. degrees in electrical and electronic engineering from the Tokyo Institute of Technology, Tokyo, Japan, in 2008, 2011 and 2014, respectively. He was a Research Fellow of the Japan Society for the Promotion of Science (JSPS) in 2013. From 2014 to 2017, he worked at Mitsubishi Electric Corporation, Tokyo and was engaged in research and development of aperture antennas for satellite communications and radar systems. From 2017 to 2019, He was a Specially Appointed Assistant Professor at the Tokyo Institute of Technology, Tokyo. He is currently an Assistant Professor there. His research interests include electromagnetic analysis, aperture antennas and planar waveguide slot array antennas.

Dr. Tomura received the Best Student Award from Ericsson Japan in 2012 and the IEEE AP-S Tokyo Chapter Young Engineer Award in 2015 and Young Researcher Award from IEICE technical committee on antennas and propagation in 2018. He is a member of IEEE and IEICE.

Our Research Interests

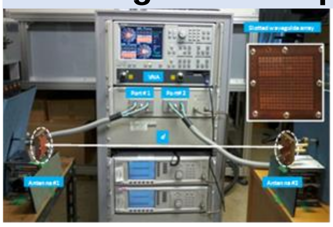
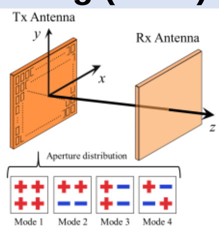
Hirokawa laboratory have researched antennas, feeding circuits, electromagnetic analysis theory and wireless communication systems. Main target frequency band is millimeter wave band and higher band such as 120 GHz and 350 GHz. The features of our antennas are planar, high gain, high efficiency and wide bandwidth, which have been realized by new fabrication method such as diffusion bonding of thin laminated metal plates and 3d-printer. Not only components but also wireless communication system has been studied such as 60-GHz band gigabit access transponder equipment (GATE) and rectangular coordinate orthogonal multiplexing (ROM), a multiplex communication system.

Post-wall waveguide

- Known as Substrate Integrated Waveguide (SIW)
- Published in the IEEE transaction in 1998 (Total citation: 308, Web of Science, 2017/6)
- Used as microwave and millimeter-wave band low-loss waveguide

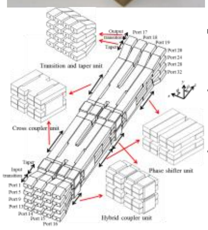
Rectangular coordinate orthogonal multiplexing (ROM)

- Published in the IEEE transaction in 2017
- Equivalent to OAM transmission in the optical communication system, and apply to microwave and millimeter-wave applications

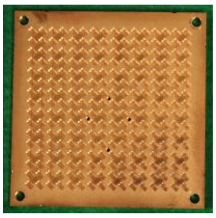
2-D beam-switching one-body Butler matrix

- Published in the IEEE transaction in 2016.
- Combined E and H-plane short-slot coupler into one body.
- Components of the Butler matrix (Hybrid and Cross coupler)

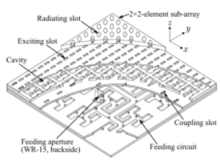


- $4^2\times4^2$-way one-body 2-D beam-switching waveguide Butler matrix
- Reduced its length and conduction losses by half.
- Reduced the number of components and volume.

Corporate-feed Slot Array Antenna with Plate-laminated Waveguide

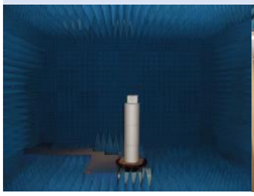


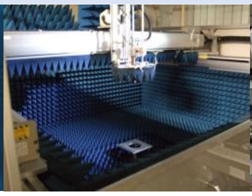
- Published in the IEEE transaction in 2011.
- After that, research is also started in Sweden, Singapore, China, etc.
- Designed in various frequency bands like 38-GHz band, 60-GHz band, and 120-GHz band, etc.



✓ Large number of elements
⇒ High gain
✓ Made with metal only
⇒ High efficiency
✓ Composed of the corporate-feed circuit
⇒ Wide band

Measurement Facility


Anechoic Chamber


Near Field Measurement


Vector Network Analyzer

- Antennas are made and measured in the practically used frequency band.
- Specialized to planar antenna.(by 110GHz)

○Anechoic Chamber : Gain, Radiation Pattern
○Near Field Measurement :
Aperture Distribution (AM, PH)
Directivity, Radiation Pattern
○Network Analyzer : Reflection

Hirokawa Laboratory

Design of a Circularly Polarized Parallel-plate Slot Array Antenna with Corrugations

Parallel-plate slot array antennas have a simple structure and high efficiency in the millimeter wave band. When excitation of circularly polarized waves is performed using inclined slots, the slots are arranged at an angle to the plane waves propagating in the parallel plate, causing scattering waves in the transverse direction, which deteriorates the characteristics. We have designed a circularly polarized parallel-plate slot array antenna with a corrugation structure that prevents laterally scattered waves.

Figure 1 shows the antenna structure. The antenna has a two-layer structure and measures 100 mm square. The lower layer has a feeding waveguide in the center. The feeding waveguide consists of seven elements on each side, which are excited by an inclined feeding slot in the center of the wide wall and whose reflections are suppressed by the posts. A corrugated waveguide with post walls is installed at both ends of the feed waveguide in the lower layer of the antenna structure shown in Figure 1. The corrugated structure is periodically installed in the parallel-plate waveguide to suppress scattered waves. The upper layer of the antenna structure shown in Figure 1 has a radiating section. It consists of a two-dimensional array of circularly polarized slot-pair elements with two slots of the same length inclined at ±45 degrees to the plane wave and spaced 1/4 wavelength apart.

In the direction parallel to the feed waveguide, the amplitude and phase were almost uniform, but in the perpendicular direction, the amplitude and phase were tilted by about 10 dB and about 60°, respectively, which should be improved in the future. The reflection is slightly larger at 26.5 GHz to 27.5 GHz, at about -8 dB, but the axial ratio is good at about 1dB.

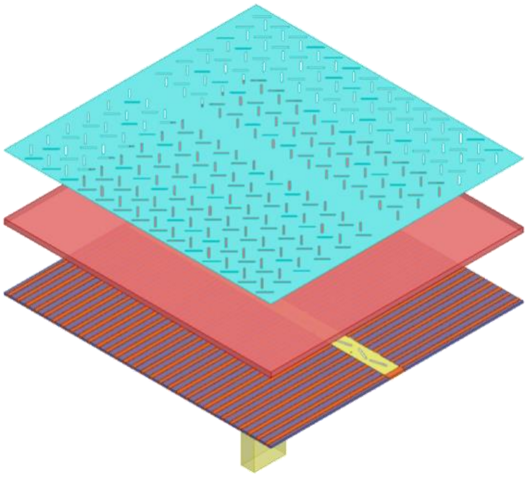


Fig. 1 Antenna Structure

Reference

[1] Y. Tomori, T. Tomura and J. Hirokawa, “Design of a Circularly Polarized Slot Array on a Parallel-plate Waveguide fed by Longitudinal Coupling Slots with Posts”, International Symposium on Antennas and Propagation (ISAP), Jan. 2021.

[2] 友利優希,戸村崇,広川二郎, “円偏波放射コルゲーション付平行平板スロットアレーアンテナの設計”, 電気情報通信学会総合大会,B-1-68, 2023-3.

Design of a Center-fed Dual-polarized Parallel Plate Waveguide Slot Array Antenna

Parallel plate waveguide slot array antennas have high antenna efficiency and simple structure, which makes them suitable for high power and mm-Wave applications. A waveguide feeder for using conventional tilted coupling slots and inductive walls was proposed in [1] to feed a parallel plate waveguide slot array antenna. In [2], a dual-polarized parallel plate waveguide slot array antenna using conventional waveguide feeders was proposed. A waveguide feeder using centered longitudinal coupling slots was proposed in [3] for a parallel plate waveguide antenna, with enhanced radiation performance.

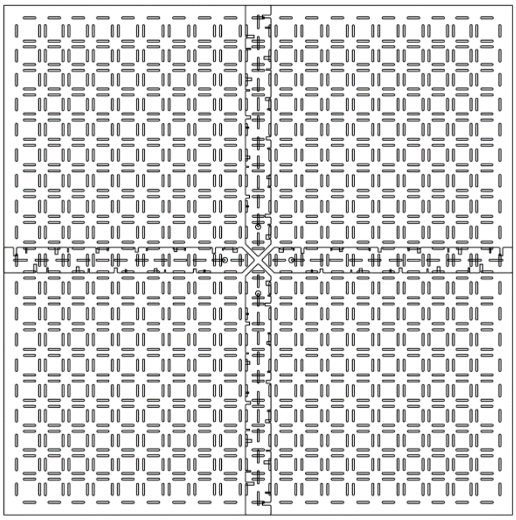


Fig. 1. Antenna Structure.

The structure of the proposed antenna is shown in Fig. 1. On the top is a radiating panel using aligned slot pairs surrounded by metal walls, under which are four 12-element probe-fed waveguide feeders using centered longitudinal coupling slots and inductive walls. The feeding points are placed between the first and the second elements because of the limit of the connectors. The size of the radiating panel is 213 mm×213 mm×5 mm, and expanded dielectric substrate (ε_r = 1.12) is used for it.

The simulation of the waveguide feeder shows that both the working bandwidth and the field distribution consistency inside the parallel plate waveguide have been enhanced compared to the conventional waveguide feeder with tilted coupling slots.

The working frequency range of the dual-polarized antenna is 23.45 GHz – 25.41 GHz (8.02%). The gain of the antenna at 24.5 GHz is 34.33 dBi and the aperture efficiency is 71.31%. Compared to the antenna with conventional waveguide feeders, the gain at 24.5 GHz is increased by 2.8 dBi, and the aperture efficiency is increased by 34.40%.

Reference

[1] T. Wang, T. Tomura, and J. Hirokawa, “Analysis of Coupling Slots with a Reflection-canceling Wall for Parallel Plate Slot Array Antenna,” Intl. Symp. Antennas Propag., TA1P-1, Oct. 2019.

[2] J. Hirokawa et al., “Feasibility of Dual-Polarized Waveguide-Fed Slot Array Antenna,” IEICE Spring Conf., B-112, Mar. 1992.

[3] T. Wang et al., “Design of Longitudinal Coupling Slots with Matching Walls for a Rectangular Parallel Plate Slot Array Antenna,” Intl. Symp. Antennas Propag., 2D3.7-195, Jan. 2021.

Hirokawa Laboratory

Air-Filled Gap Waveguide with Interleaved Pins for Higher-Frequency Fabrication

Gap waveguide (GW) is a metamaterial-based wave-guiding structure that employs a periodic electromagnetic bandgap geometry, such as "bed of nails", around a certain type of guiding path, for example, ridge or groove, allowing electromagnetic waves to be steered and controlled in a parallel-plate structure. Air-filled GW such as ridge GW and E- and H-plane groove GW provides low conductor loss and high power-handling capability. All these GWs can be realized without the need for metal contact between the upper and lower metal surfaces, therefore, it can avoid expensive brazing or bonding costs. However, "bed of nails" would be difficult to fabricate especially at extremely high frequency and if the pins are closely spaced and thin. To overcome this issue, we introduced a new groove GWG technology where interlaced pins that come from both top and bottom plates, which can enhance space utilization and increase the distance between the pins in the same plate [1].

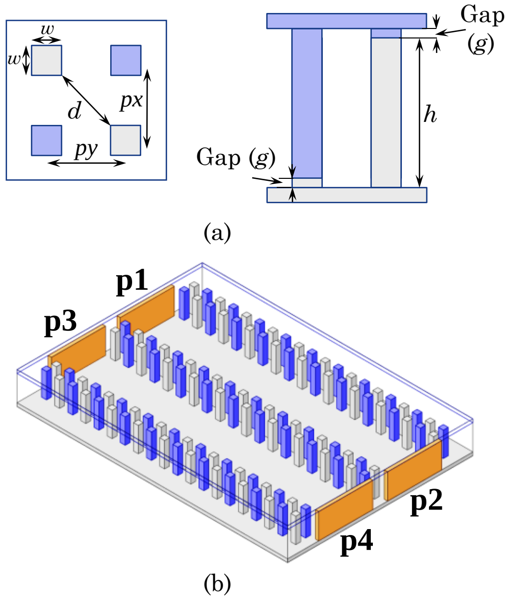


Fig. 1. (a) Unit cell with interlaced square pins and (b) two parallel groove gap waveguides with interlaced square pins.

Fig. 1(a) shows the unit cell with proposed 2×2 interleaved square pin. The center-to-center spacing of the pins is p_x or p_y, and the period of the unit cell is two times p_x or p_y in the x- or y-directions. Since the pins on the same board are positioned along the diagonal direction, the minimum distance d between the pins on the same plate is moved in the diagonal direction. Therefore, the proposed design enables the spacing between the pins on the same plate to be substantially enlarged in comparison to the traditional design where all pins from the same plate [2]. The proposed and conventional unit cell with the same parameters are designed to ensure that the bandgap is located at the V-band. The dispersion diagram of the proposed unit cell is analyzed by HFSS. The upper frequency of the bandgap for proposed and conventional unit is about 95 GHz. In contrast, the lower frequency of the bandgap for the proposed unit cell is increased by 5 GHz than that for the conventional unit cell. Although the stopband of the proposed unit cell is reduced, it still has almost 54 GHz bandwidth.

The proposed unit cell with interleaved pins is applied in two parallel H-plane groove GWs for demonstration as shown in Fig. 1(b) [3]. The reflection is almost less than -20 dB except for the frequency around 50 GHz, and the transmission is close to 0 dB when the frequency increases. However, the crosstalk of the waveguides with interlaced pins is higher than the H-plane groove GWs with conventional unit cell, especially for port 1 and 4. When the frequency declines, isolation of the proposed waveguides decreases, but is still less than -20 dB from 50.6 GHz.

[1] Y. Wu et al., URSI Radio Science Letters, vol. 4, 2022.
[2] Y. Wu et al., IEICE Society Conf., B-1-77, 2022.
[3] Y. Wu et al., Intl. Symp. Antennas Propag., pp. 567-568, Oct. 2022.

Design of a waveguide two-plane coupler with a different division ratio in horizontal and vertical directions

In the past several years, applications of multi-beam antennas have been increasingly valued in 5G communication. Multi-beam feeding networks like Butler matrix, as of now, are still dominant in practical applications. Many efforts have been made to miniaturize the 2D Butler matrix in physical size and topological constitution. In 2016, Kim et al. firstly proposed a two-plane hollow waveguide coupler, having a bright advantage over a conventional one-plane structure in shorter physical length. However, when it comes to more complex multi-beam matrix networks, apart from equal division ratio hybrid coupler and crossover, some sorts of unequal division couplers are in demand as well. This manuscript gives an introduction to a new two-plane coupler with a different division ratio in the horizontal and vertical directions and follows its performance in terms of amplitude and phase difference from 27.65GHz to 28.85GHz, with 4.1% fractional bandwidth.

This two-plane coupler is symmetrical to the x-axis, y-axis, and z-axis. It should be noted symmetry along the z-axis is not obligatory yet this yielding will bring about worthy simplification in the superfluous process of electromagnetic numerical calculation. The two-plane coupler is generally equivalent to cascading sections of two vertically-stacked H-plane couplers and two horizontally-stacked E-plane couplers. The output S-parameters are in terms of amplitude and phase corresponding to incidence from Port 1 along with the bandwidth from 27.65GHz to 28.85GHz, with 4.1% fractional bandwidth. The deviation of amplitudes normalized in decibel from the desired theoretical value doesn't exceed ±0.8dB. S61 and S81 are almost consistence, with 3dB extra superiority over synchronous S51and S71. While the degradation of relative phase difference among Port 6, Port 7, and Port 8 compared with Port 5 is no more than ±15 degree compared with ideal distribution in -90 degree and -180 degree.

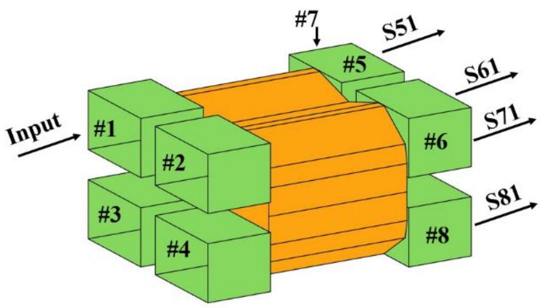


Fig. 1 Coupler structure

Referrence

[1] D. Kim, J. Hirokawa, and M. Ando. "Design of Waveguide Short-Slot Two-Plane Couplersfor One-Body 2-D Beam-Switching Butler Matrix Application," IEEE Trans. Microw. Theory Tech., vol. 64, no. 3, pp. 776-784, Mar. 2016.

[2] J. Hirokawa, and N. J. G. Fonseca, "Generalized One-Dimensional Parallel Switching Matrices With an Arbitrary Number of Beams," IEEE J. Microw., vol. 1, no. 4, pp. 975-988, Oct. 2021

Hirokawa Laboratory

Comparative Evaluation of Different Assignments for Post-wall 1-D Parallel Switching Matrices with Four Beams

General configurations of 1-D parallel switching matrices with an arbitrary number of beams have been proposed [1]. The configurations overcome the shortcomings of the Butler matrix and the Nolen matrix, which are having limited number of beams and having imbalance among outputs. A special configuration having an even number of beams, where two Nolen matrices are fed in parallel through crossovers, has a more compact structure compared with standard 1-D matrices.

The block diagram and the realized structure of the case of four beams are shown in Fig. 1. The structure is modified according to [2]. It has a symmetrical structure and is composed of four hybrid couplers, two cross couplers, and four phase shifters. The design is realized by post-walls and uses a PTFE substrate, which has a thickness of 3.2 mm and a dielectric constant of 2.17. For this structure, there are eight special assignments for assigning phase differences between adjacent output ports to determine beam directions. Two typical assignments are selected. Assignment 1 has the smallest absolute values of phase shift, which should have the widest bandwidth among the eight assignments. Assignment 5 is the well-known conventional configuration coming from the Fast Fourier Transform concept. Assignment 1 uses two -34.34° and two -79.34° phase shifters. Assignment 5 uses two 55.66° and two 100.66° phase shifters. In order to do measurement, the structures of transitions are added to both sides of the matrix. The transitions are designed based on the coaxial-to-waveguide transformers WR-42.

According to the simulation results, in the case of Assignment 1, the two outer ports have the reflection less than -15 dB over 10.86%, and the two inner ports have the reflection less than -13.42 dB over 12.05%. The average phase differences between adjacent output ports at the center frequency are -135.14°, 44.87°, -45.26°, and 134.78°, compared with the theoretical values of -135°, 45°, -45°, and 135°. For Assignment 5, the bandwidths of reflection less than -15 dB for the two outer ports and the two inner ports are 9.50% and 7.91% respectively. The average phase differences are -44.87°, 135.90°, -135.26°, and 45.51°. Though the errors of the average phase differences are close, Assignment 1 has a wider bandwidth compared to the conventional configuration, Assignment 5, as expected.

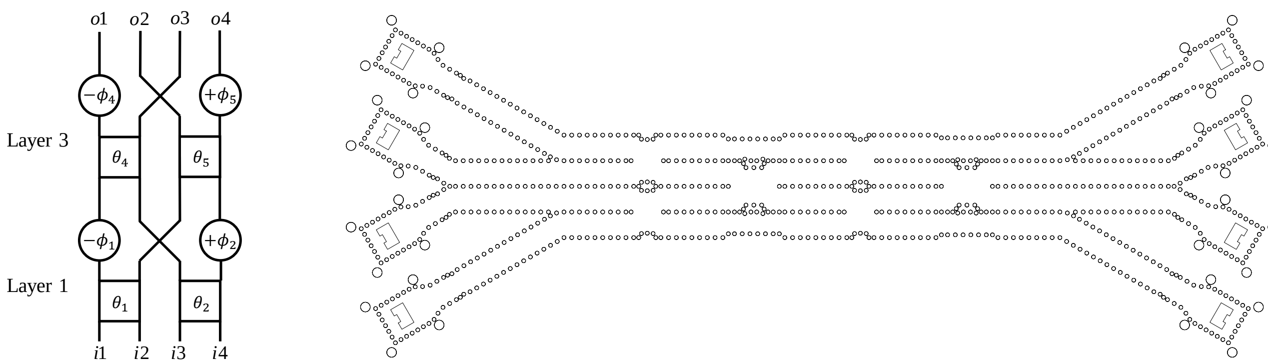


Fig. 1. Block Diagram and Realized Structure of Matrix

Reference

[1] J. Hirokawa and N. J. G. Fonseca, "Generalized one-dimensional parallel switching matrices with an arbitrary number of beams," *IEEE J. Microw.*, vol. 1, no. 4, pp. 975–988, Oct. 2021. DOI: 10.1109/JMW.2021.3106871

[2] J. Hirokawa and N. J. G. Fonseca, "Special assignments of adjacent output phase differences per input ports in generalized one-dimensional parallel switching matrices," *IEICE Commun. Express*, vol. 11, no. 6, pp. 268–272, Jun. 2022. DOI: 10.1587/comex.2022SPL0010

Design of Reconfigurable Reflectarray Antennas on Flexible Substrate with Varactor Diodes Mounted on Slot-Coupled Microstrip Lines

Compact deployable antennas are suitable for small satellites that require strict payload constraints. In particular, reflectarray antennas on flexible substrate[1] are expected to be used as large antennas for small satellites because they can be combined with a large deployable membrane structure[2] to improve storage efficiency dramatically. On the other hand, flexible substrates with low flatness can be deformed relatively easily due to creases for storage or external forces, which causes radiation phase error between array elements and gain reduction. Therefore, it is necessary to dynamically control the radiation phase. In this study, we design a reconfigurable reflectarray antenna with varactor diodes on flexible substrate[3]. Fig. 1 shows the proposed antenna structure. The first layer consists of radiation slots and slot-coupled microstrip lines with diodes mounted on it. The second layer is a ground plane to prevent the transmission of the incident wave to the backside of the reflector. In this structure, reconfigurability is realized by controlling the reverse bias voltages applied to diodes on the first layer. In the design process, periodic boundary conditions in the x and y-axis directions and x-polarized normal incident wave are assumed, and the voltage characteristics of the reflection coefficient S_{11} are analyzed by finite element method. For modeling the diode(Macom, MA46603-276), measured S-parameters for each reverse bias voltage are used. As a result, it is confirmed that a variable reflection phase range of 343 deg. could be obtained with a reflection loss of 0.53 dB or less.

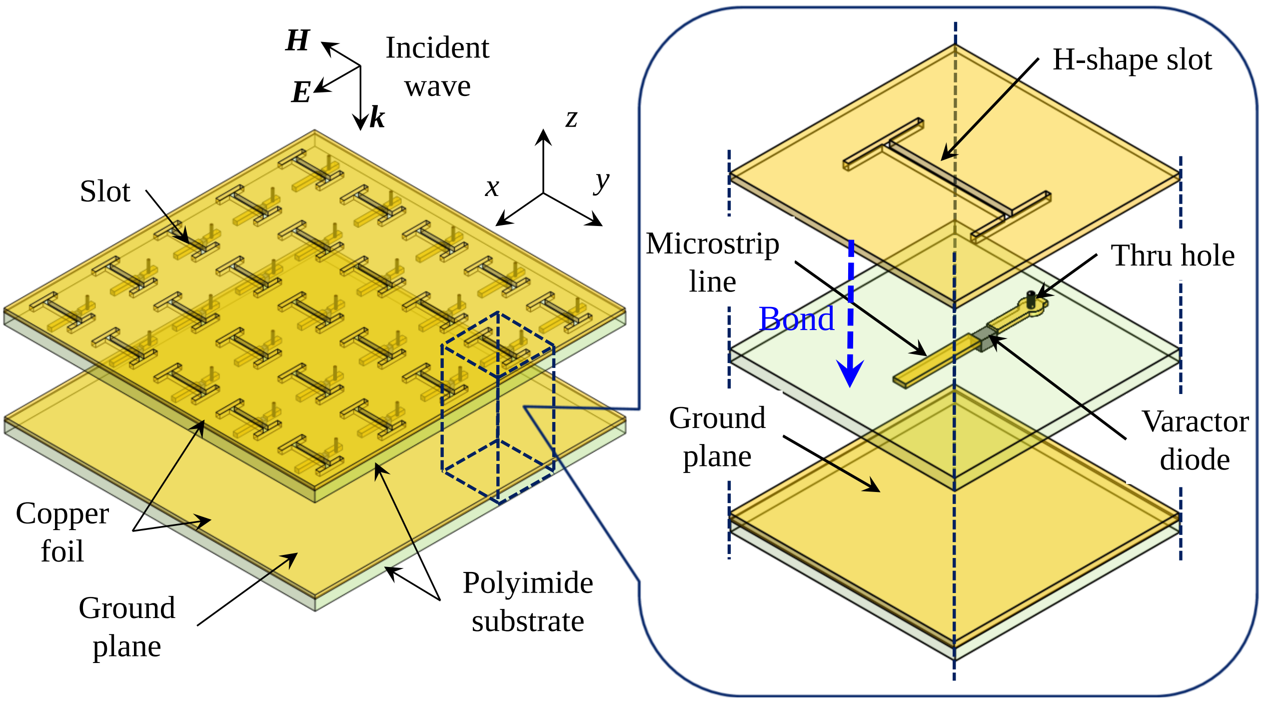


Fig. 1 Antenna structure

Reference

[1] T. Tomura et al, “Simulation results of a foldable reflectarray composed of four triangular notched patches,” Int. Symp. Antennas Propag., pp.1-2, 220358, 2021.

[2] K. Ikeya, et al., “Significance of 3U CubeSat OrigamiSat-1 for space demonstration of multifunctional deployable membrane,” Acta Astronautica, vol.173, pp.363-377, 2020.

[3] 武田裕貴，戸村崇，坂本啓，“スロット結合線路にバラクタダイオードを実装した反射位相可変フレキシブル基板リフレクトアレーの設計”，信学技報，vol. 122, no. 441, AP2022-250, pp. 93-96, Mar. 2023.

Okada Laboratory / Shirane Laboratory

Okada Laboratory Home page: http://www.ssc.pe.titech.ac.jp/

Professor Kenichi Okada

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Prof. Okada is a member of the Institute of Electrical and Electronics Engineers (IEEE), the Institute of Electronics, Information and Communication Engineers (IEICE), the Information Processing Society of Japan (IPSJ), and the Japan Society of Applied Physics (JSAP). He was a recipient or co-recipient of the Ericsson Young Scientist Award in 2004, the A-SSCC Outstanding Design Award in 2006 and 2011, the ASP-DAC Special Feature Award in 2011 and Best Design Award in 2014 and 2015, the MEXT Young Scientists' Prize in 2011, the JSPS Prize in 2014, the Suematsu Yasuharu Award in 2015, the MEXT Prizes for Science and Technology in 2017, the RFIT Best Paper Award in 2017, the IEICE Best Paper Award in 2018, the RFIC Symposium Best Student Paper Award in 2019, the IEICE Achievement Award in 2019, the DOCOMO Mobile Science Award in 2019, and more than 50 other international and domestic awards. He is/was a member of the technical program committees of IEEE International Solid-State Circuits Conference (ISSCC), VLSI Circuits Symposium, and European Solid-State Circuits Conference (ESSCIRC), Radio Frequency Integrated Circuits Symposium (RFIC), Asian Solid-State Circuits Conference (A-SSCC), and he also is/was Guest Editors and an Associate Editor of IEEE Journal of Solid-State Circuits (JSSC), an Associate Editor of IEEE Transactions on Microwave Theory and Techniques (T-MTT), a Distinguished Lecturer of the IEEE Solid-State Circuits Society (SSCS). He is an IEEE Fellow.

Professor Hiroyuki Sakai

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LSI technologies at some Laboratories of Panasonic Corporation.
In 2020, he joined Tokyo Institute of Technology as a Creative Manager of Open Innovation Platform. He is now a Specially Appointed Professor of Electrical and Electronic Engineering at Tokyo Institute of Technology, Tokyo, Japan. Prof. Sakai is a Senior Member of the Institute of Electrical and Electronics Engineers (IEEE). He was a Secretary of the IEEE Electron Devices Society Kansai Chapter from 2002 to 2003, a member of the Technical Program Committee of the IEEE International Solid-State Circuit Conference from 2002 to 2008.

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Okada Laboratory / Shirane Laboratory

A 32kHz-Reference 2.4GHz Fractional-N Nonuniform Oversampling PLL with Gain Boosted PD and Loop Bandwidth Calibration

A 32.768kHz-reference (REF) phase-locked loop (PLL) can help eliminate the high frequency crystal oscillator in a wireless system-on-chip (SoC), which would significantly reduce the cost and improve power efficiency. To break the limitation of the narrow bandwidth and poor jitter caused by low REF frequency (f_{REF}), the reference-oversampling PLL (OSPLL) was studied. However, the 32kHz-REF PLL severely suffers from jitter transferred from voltage noise due to slow signal slope. To overcome this issue, a nonuniform OSPLL is proposed with a 32kHz REF.

Fig. 1. shows the former uniform sampling method in OSPLL and the proposed non-uniform sampling method. With the slew rate of REF (S_{REF}) relationship from voltage noise to jitter, the small S_{REF} at sine REF peak induces a large jitter. The uniformly distributed phase-detection clock (CLK_{PD}) samples the noisy peak and degrades the overall jitter performance. To address the above issues, the proposed nonuniform OSPLL changes the sampling frequency based on the S_{REF}, which avoids the noisy slow-slope peak of the sine REF and the voltage-noise-induced jitter can be suppressed.

Figure. 2 shows the detailed block diagram of the proposed nonuniform OSPLL. The coarse PLL operates with the dead zone (DZ) included in the phase frequency detector (PFD) is automatically turned off when the fine PLL is locked. The fine PLL directly uses the 32kHz sine REF without any buffers. V_{DAC} is generated by a RDAC whose control code CDAC[n] is generated by the look-up-table (LuT)-based calibration block and triggered by the nonuniform feedback clock (CLK_{FB}). The 33MHz CLKbase is generated from DCO via MMD then decimated by the nonuniform select pulse with a DFF to generate CLK_{FB}, which corresponds to the 256-oversampling ratio (OSR) in a 32kHz REF period. CLK_{PD} is generated from CLK_{FB} via DTC with the time delay $t_{DTC,n}$ at the nth sampling point. The DTC consists of coarse and fine DTCs. The ranges of the coarse and fine DTCs are 106ns and 1.3ns, with resolution of 414ps and 1.2ps respectively. As the bottom part of Fig. 2 shows, in the proposed nonuniform OSPLL, the constructed DAC voltage (V_{DAC}) is shaped with a high slope (S_{DAC}) in the gain-boosted PD, a high S_{DAC} is achieved by generating a slope on VDAC in the gain-boosted PD.

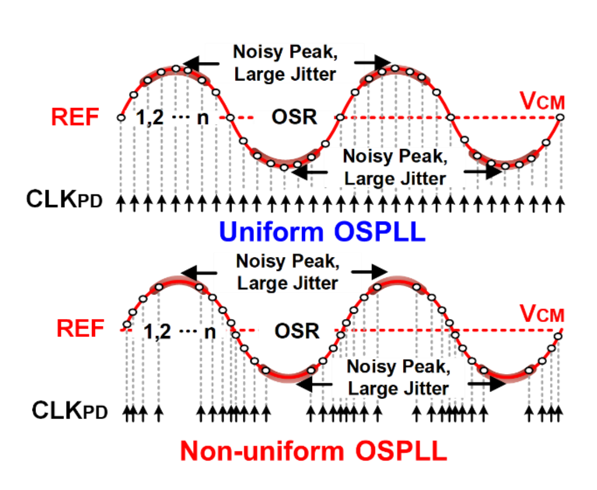


Fig. 1. Proposed nonuniform OSPLL.

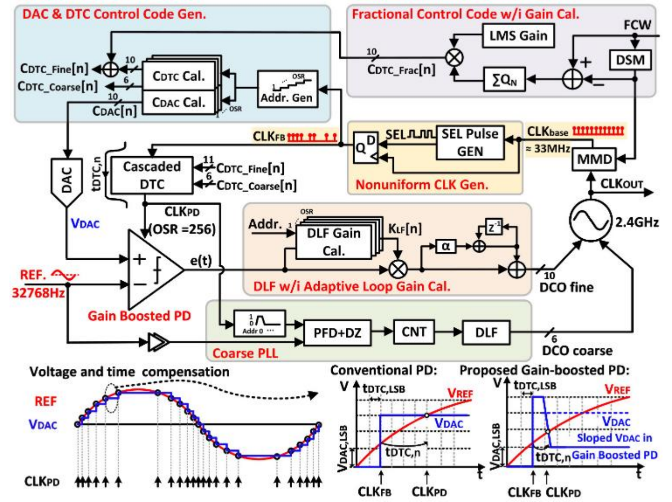


Fig. 2. Overall architecture of proposed OSPLL.

Fig. 3 illustrates the proposed gain-boosted PD. To relieve large voltage induced jitter in the PD, the sloped V_{DAC} is generated to increase PD gain (K_{PD}). The S_{DAC} is near -120000V/ms at the 0-degree phase which corresponds to a near 2ps rms $\Delta t_{VN,PD}$. With the gain-boosted PD, S_{DAC} can help suppress $\Delta t_{VN,PD}$ effectively without increasing f_{REF}. The time-and-voltage noise model is shown at the bottom.

Fig. 4 shows the measured phase noise, and the rms jitter integrated from 10kHz to 10MHz is 4.95ps. The REF spur is -79dBc while worst-case fractional spur is measured as -43dBc. Fig. 5 provides a comparison to prior art and a die micrograph of the proposed nonuniform OSPLL, fabricated in a 65nm CMOS technology with an active area of $0.59mm^2$. The total power consumption is 3.8mW from a 1V supply. The presented work guarantee performance with an FoM of-220.3dB and FoM_{REF} of -255.2dB.

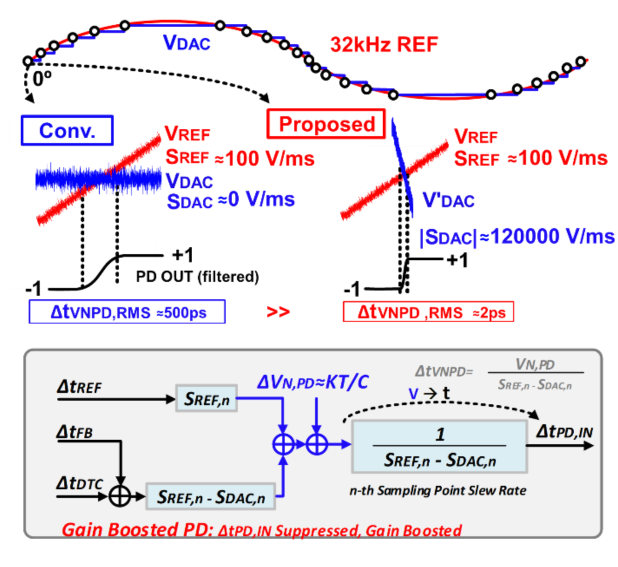


Fig. 3. Proposed mismatch comp. circuits.

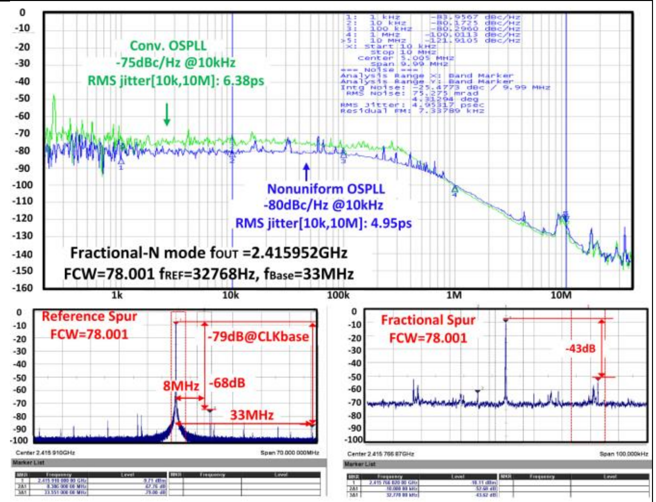
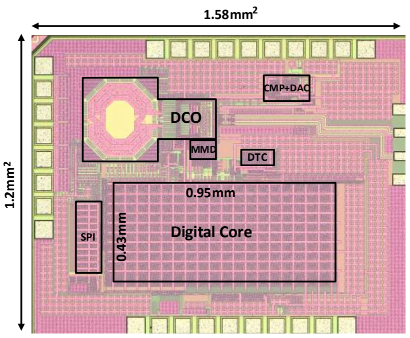


Fig. 4. Measured constellations and EVMs.



	Power (mW)	Active Area (mm^2)
DCO	1.1	0.151
DAC	0.62	0.011
DTC	0.08	0.015
CMP	0.08	0.004
Digital Core	1.92	0.409
Total	3.8	0.59

	This Work	JSSC'15 A. Lahiri[1]	JSSC'21 J.Seol[2]	JSSC'21 J.Du[10]	ISSCC'21 J. Qiu[11]	ISSCC'18 H. Liu[7]	VLSI'20 L. Wu[8]
Technology	65nm CMOS	28nm FDSOI	28nm CMOS	28nm CMOS	65nm CMOS	65nm CMOS	130nm CMOS
Output (GHz)	2.0 to 2.8	0.96	4	1.8 to 2.3	2.0 to 2.8	2.0 to 2.8	2.99 to 3.5
Reference (MHz)	0.032768	0.032768	200	48	0.032768	26	80
Loop BW(MHz)	0.2	0.002*	20*	1*	0.2	1*	3*
Loop BW/FREF	6.25	0.0625	0.1	0.02	6.25	0.0385	0.0375
OSR	256	1	20	1	256	2	1
Oversampling Method	Non-uniform+ Gain Boosted PD+ Adaptive BW Cal.	Uniform + ADC	Uniform + Multi-PDs	Ref. Doubler	Uniform + Cosine BW	Ref. Doubler	IDAC+ADC
Frac-N/Int-N?	Frac-N	Int-N	Int-N	Frac-N	Frac-N	Frac-N	Frac-N
Jitter(ps) Integ. Freq(Hz)	4.95 (10k-10M)	523 (20-20k)	0.067 (10k-100M)	0.414 (10k-100M)	5.79 (10k-10M)	0.53 (10k-10M)	0.101 (10k-40M)
Core Area² (mm)	0.59**	0.15	0.17	0.24	0.576	0.23	0.27
Power (mW)	3.8	0.486	5.2	1.15	4.97	0.98	9.2
Ref. Spur (dBc)	-68	-65	-78.1	-72	-78	-72	-79
Frac. Spur (dBc)	-43	N.A.	N.A.	-49	-36	-56	-56
FoM*** (dB)	-220.23	-188.7	-256.3	-247	-217.8	-246	-250.3
FoMREF**** (dB)	-255.5	-223.5	-253.3	-250	-252.6	-251.4	-251.2

FoM= 20log(Jitter/1s)+10log(Power/1mW) *FoM_{REF} =FoM +10log(F_{REF}/100MHz)

*Estimated from measurement **Both uniform and non-uniform operation included

Fig. 4. Comparison Table.

Okada Laboratory / Shirane Laboratory

A Bi-Directional 300-GHz-Band Phased-Array Transceiver in 65-nm CMOS With Outphasing Transmitting Mode and LO Emission Cancellation

Frequencies above 200 GHz are among the strongest candidate bands to be utilized in beyond 5G wireless communication systems where very high data rates and low latency are required. This work introduces a four-element 300-GHz band bi-directional phased-array transceiver (TRX) in CMOS. The TRX utilizes the same antenna, signal path, and local oscillator (LO) circuitry to operate either in transmitter (TX) mode or receiver (RX) mode.

Fig. 5 shows the block diagram of the proposed 300-GHz-band TRX system. It consists of two mixing paths with a bi-directional subharmonic mixer and a bi-directional IF distributed amplifier forming each path. The LO chain includes three phase shifters, two frequency quadruplers, and LO buffers to control the beam direction and generate the required LO frequency. The TX mode utilizes outphasing technique to increase output power and cancel LO feed-through, while the RX mode benefits from LOFT cancellation technique to suppress LO emission and reject the image signal from TX. The applied LO frequency is 30 GHz, and it becomes 240 GHz at the RF end after frequency multiplication and subharmonic mixing. The RF channel is selected by adjusting the IF center frequency.

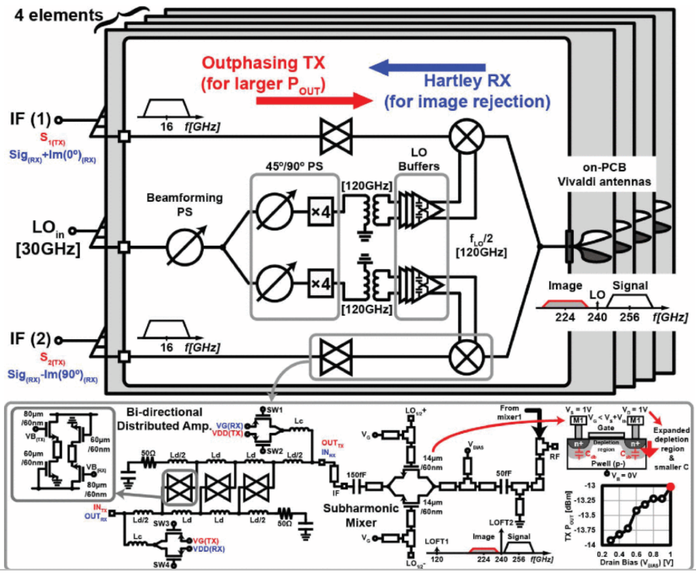


Fig. 5. Block diagram of 300GHz-band CMOS bi-directional phased-array TRX system.

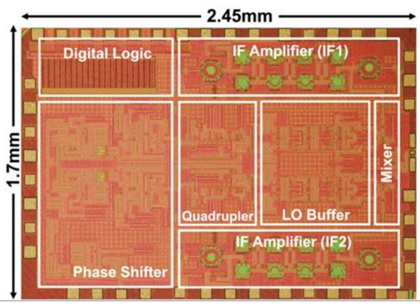


Fig. 6. Die micrograph

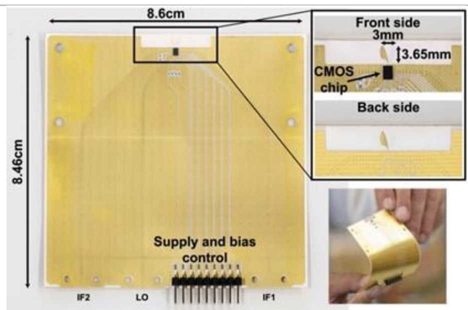


Fig. 7. Photographs of PCB used for phased-array implementation

Fig. 6 shows the die micrograph fabricated in 65-nm CMOS process. The antennas are printed on PCBs and the connection with CMOS is designed using the flip-chip. The detailed photographs of the flexible 50-µm LCP PCB are shown in Fig. 7.

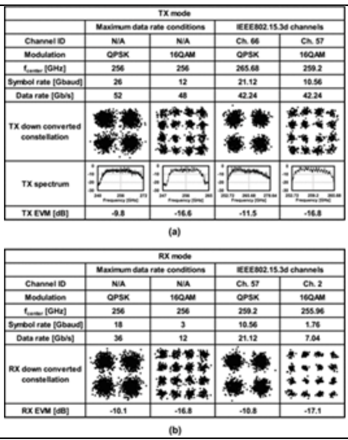


Fig. 8. Measured EVM and constellations of (a) TX mode and (b) RX mode.

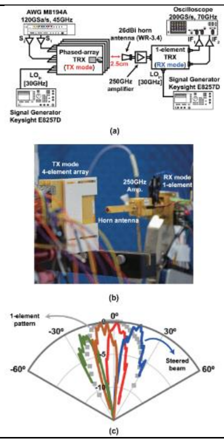


Fig. 9. Array pattern measurement setup: (a) block diagram and (b) photograph. (c) Measured steered beam pattern.

The summary of 1-element on-wafer evaluation is shown in Fig. 8. At IF center frequency of 16 GHz, The TX-mode achieved a maximum data rate of 52 Gb/s using QPSK and 48 Gb/s using 16QAM. Meanwhile, the RX-mode achieved a maximum data rate of 36 Gb/s at an RF center frequency of 256 GHz. The TRX consumes around 750mW DC power for both TX mode and RX mode. The performance of four-element phased-array is evaluated using a setup shown in Fig. 9(a) and Fig. 9(b). The measured beam pattern shown in Fig. 9(c) demonstrates steering range in the H-plane from -18∘ to 18°.

In Fig. 10, this work is compared with several state-of-the-art 300-GHz-band TRXs. The bi-directional architecture reduces the area considerably and the mixer-distributed-amplifier combination contributes to the very wide bandwidth.

	Process	Freq. [GHz]	Structure	Antenna sharing	TX topology	Max. baud rate [Gbaud]	P_{DC}[W]	Area [mm^2]
IMS '20 [16]	130nm SiGe	240	Single-element	No	Single-stream / power amplifier	25 (16QAM)	TX:1.24 RX:0.85	TX:7 RX:5.1
MWCL '19 [14]	130nm SiGe	230	Single-element	No	Single-stream / power amplifier	23.75 (16QAM)	TX:0.96 RX:0.45	TX:1.5 RX:1.25
JSSC '20 [3]	80nm InP-HEMT	290	Single-element	No	Single-stream / power amplifier	30 (16QAM)	TX:4.5* RX:4.5*	TX:2.44 RX:2.44
JSSC '15 [27], [28]	65nm CMOS	240	Single-element	No	Single-stream / tripler-last	TX:8 (QPSK) RX:8 (QPSK)	TX:0.22 RX:0.26	TX:2 RX:2
ISSCC '17 [30] & IMS '17 [31]	40nm CMOS	290	Single-element	No	Power combining	TX:21 (32QAM) RX:14 (QPSK)	TX:1.4 RX:0.65	TX:5.19 RX:3.15
JSSC '19 [32]	40nm CMOS	266	Single-element	No	Power combining	20 (16QAM) TX:28 (16QAM) RX:N/A	TX:0.89 RX:0.9	TRX:11
IMS '20 [33]	65nm CMOS	288	Single-element	No	Single-stream / mixer-last	17 (QPSK)	TX:0.27 RX:0.14	TX:1.9 RX:1.9
JSSC '14 [26]	32nm SOI CMOS	210	Combining-array	No	Single-stream / PA-last	Not measured#	TX:0.24 RX:0.07	TX:3.5% RX:1.1
This Work	65nm CMOS	256	**Phased-array$ / bi-directional**	**Yes**	Outphasing	8 (QPSK) TX:26 (QPSK)† RX:18 (QPSK)†	TX:0.75 RX:0.75	**TRX:4.17**

* Without LO multiplier. $ Only CW performance tested. † Direct connection to waveguide. # Only OOK. % Four elements total area.

Fig. 10. Performance Comparison With State-of-the-Art 300-GHz-Band TRXs

Okada Laboratory / Shirane Laboratory

A 2.95mW/element Ka-band CMOS Phased-Array Receiver Utilizing On-Chip Distributed Radiation Sensors in Low Earth Orbit Small Satellite Constellation

Small satellite technology has the potential to further extend the current satellite constellation in low earth orbit (LEO) by realizing a wider coverage and more robust networks all over the world. Compared with conventional satellites, small satellites can drastically reduce launch costs and increase the number of satellites in LEO.

Fig. 13 shows the system block diagram of the proposed low-power circularly polarized beamforming receiver with on-chip TID sensors. A single path consists of a three-stage distributed current-sharing LNA, a reflective type phase shifter (RTPS), two low-loss single-port-double-throw RF switches, and a two-stage voltage-steering current-sharing variable gain amplifier (VGA). A common path

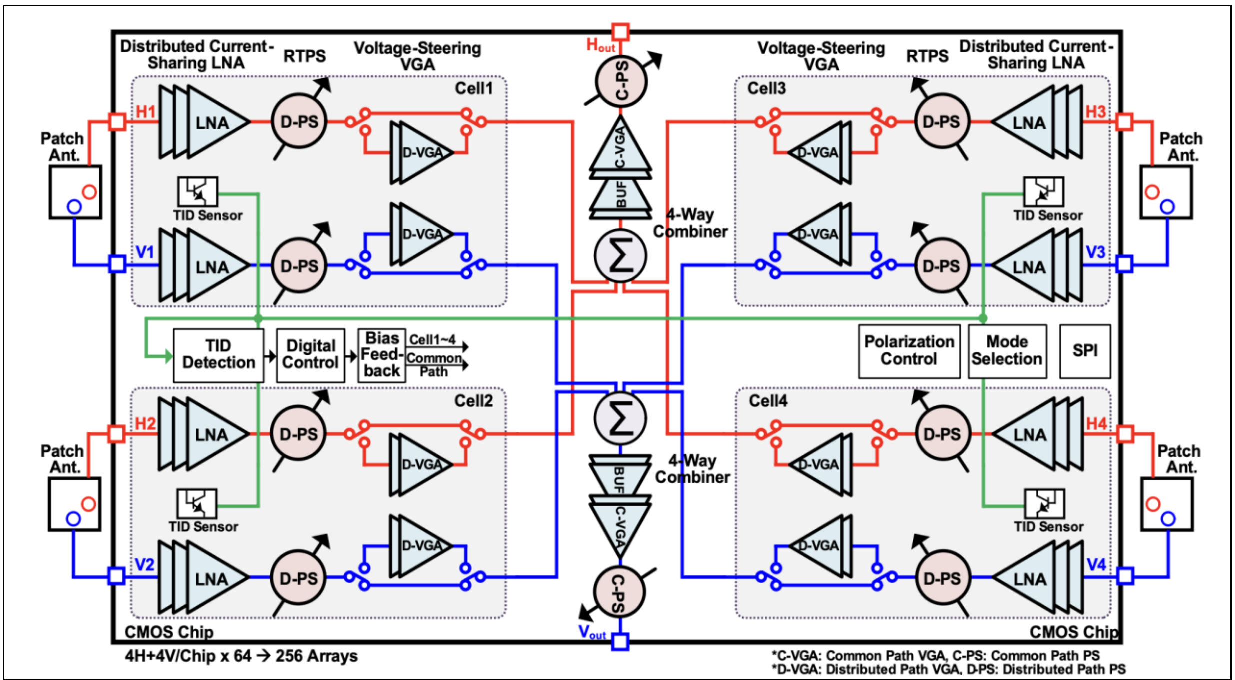


Fig. 13. System diagram of the proposed receiver.

comprises a 4:1 lumped Wilkinson combiner, a two-stage low-power buffer, a two-stage current-sharing VGA, and an RTPS. H and V signal paths are separately and symmetrically implemented in this work for supporting linear polarization, dual-linear polarization, and circular polarization modes.

As shown in Fig. 14, the locations of phased-array elements and distributed TID sensors are represented by black dots. The measured non-uniform TID values show that the proposed distributed TID sensors can detect the realistic non-uniform TID distribution. Compared to the measured gain pattern result without the compensation technique, the results with compensation show that the maximum gain variation caused by the non-uniform TID is dramatically reduced to 0.12dB for 0.5Mrad average TID.

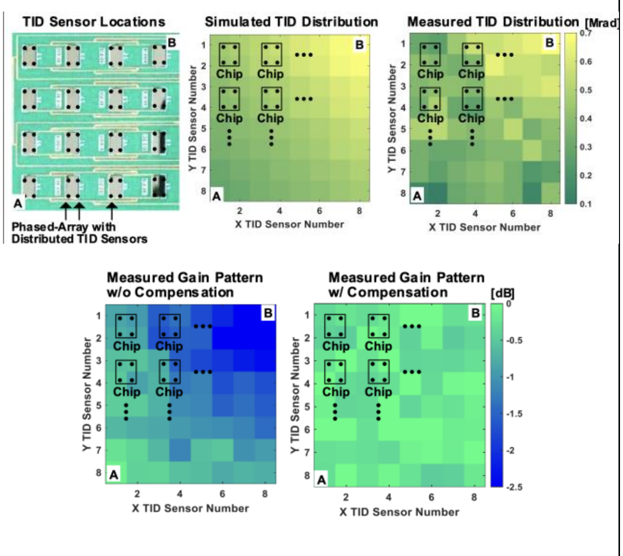
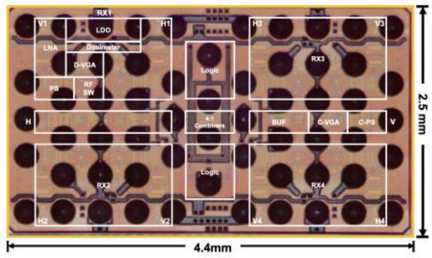
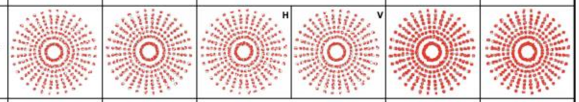


Fig. 14. Radiation compensation measured results.



Mode	H Linear Polarization	V Linear Polarization	Dual Linear Polarization (w/o MIMO Processing)		Left-Hand Circular Pol.	Right-Hand Circular Pol.
Freq.	29 GHz	29 GHz	29 GHz		29 GHz	29 GHz
Modul.	256 APSK	256 APSK	256 APSK		256 APSK	256 APSK
Symbol Rate	1.5 GBaud	1.5 GBaud	1.5 GBaud		1 GBaud	1 GBaud
Const.*			H	V		
Data Rate	12 Gb/s	12 Gb/s	24 Gb/s		8 Gb/s	8 Gb/s
EVM (RMS)^	-30.86 dB (2.86%)	-31.15 dB (2.77%)	-31.25 dB (2.74%)	-31.08 dB (2.79%)	-32.06 dB (2.49%)	-32.37 dB (2.41%)

*Measured by 64H + 64V sub-array module
^Measured EVMs are referred to the RMS magnitude

Fig. 15. Die photo and measured OTA results.

Fig. 15 shows the die micrograph, the total chip area including pads is $11mm^2$, where the single-element active area is $0.24mm^2$. The peak OTA EVM at 29GHz is -32.37dB with 1GHz 256APSK modulated signal for right-hand circular polarization mode. The highest OTA data rate of 24Gbps is achieved with a 1.5GHz dual linear polarization 256APSK modulation signal.

Fig. 16 compares this work with the state-of-the-art phased-array ICs. This work achieves 0.22dB/Mrad main lobe degradation by utilizing the on-chip TID sensor-based compensation technique.

	This work		Samsung RFIC2021[4]	Zhejiang Univ. ISSCC2021[5]	Samsung ISSCC20[6]	Tokyo Tech JSSC2021[7]	UCSD TMTT2021[8]	Tokyo Tech ISSCC2022 [1]
Process	65nm CMOS		28nm CMOS FD-SOI	65nm CMOS	28nm CMOS	65nm CMOS	Silicon Product	65nm CMOS
Application	SATCOM, 6G		5G	5G	5G	5G	SATCOM, 6G	SATCOM, 6G
Operation Band	25.9-30.1GHz		24.25-29.5GHz 37-40GHz	17.7-19.2GHz	37-40GHz	27.5-30.5GHz*	10.7-12.7GHz	26.7-30.4GHz
Integration/ chip	8xBeamformer 4H+4V RX		2xBeamformer RX	8xBeamformer RX	16xTRx IF, LO	8xBeamformer	16xBeamformer (External LNA)	8xBeamformer RX
Supply Voltage	1V		1.1V	-	0.9V/1.8V	1V	1V/2.3V	0.8V
NF	3.6dB&		4.3-6.4dB	3.2-4.1dB	4.2-4.6	5.2dB @29GHz	1.6dB&	3.8dB&
Gain	17.4dB (26dB w/ D-VGA)		29dB^	19dB^	4-47dB	19-21dB	31dB&	17dB
IIP3	-20dBm&		-37.8dBm^	-17.4dBm*	-	-20dBm*	-42dBm&	-22dBm&
P_{DC}/Element	**2.95mW&**		17.3mW&	74mW#	39mW	61mW&	45mW&	3.4mW&
Area/Element	$0.24mm^{2}$& ($0.32mm^{2}$& w/ D-VGA)		$0.46mm^{2}$&	$1.6mm^2$	$0.94mm^2$	$0.48mm^2$	$6.1mm^{2}$**	$0.196mm^{2}$&
PS Gain Error (RMS)	**0.08dB** @29GHz$		0.9dB	0.22dB	0.33dB	0.25dB @29GHz*	-	0.14dB @29GHz$
VGA Phase Error (RMS)	**0.65°** @29GHz$		-	-	-	2.3° (Variation)	-	-
OTA?	YES		NO	NO	YES	YES	NO	YES
Modulation	DVB-S2X 256APSK		64QAM OFDM	-	64QAM OFDM	256QAM OFDM	-	256APSK
Polarization Mode	Dual Linear Polarization	**Circular Polarization**	-	-	Linear Polarization	Dual Linear Polarization	Dual Linear Polarization	Linear Polarization
EVM	-31.25dB	-32.37dB	-33.1dB	-	-34.8dB	-29dB*	-	-33.2dB
Data-Rate	**24Gb/s**	12Gb/s	2.4Gb/s		4.8Gb/s	6.4Gb/s	-	12.8Gb/s
Main Beam Degradation by TID	w/o Comp. -2.4dB /Mrad	w/ Comp. **-0.22dB** /Mrad	-	-	-	-	-	-

Note: *: estimated from figure, **: estimated from package, $: w/o cal., &: single element, ^: high gain mode, #: 2 beams

Fig. 16. Performance comparison with state-of-the-art works.

Fukawa Laboratory

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received the B.S. and M.S. degrees in physics, and the Dr. Eng. degree in electrical and electronics engineering, all from Tokyo Institute of Technology, Tokyo, Japan, in 1985, 1987, and 1998 respectively. He joined Nippon Telegraph and Telephone Corporation (NTT), Japan, in 1987. Since then, he has been engaged in research on digital mobile radio communication systems and applications of the adaptive signal processing, including adaptive equalization, interference cancellation, and adaptive arrays. He was a Senior Research Engineer at NTT Mobile Communications Network Inc. (NTT DoCoMo), from 1994 to 2000, and an Associate Professor at the Tokyo Institute of Technology, from 2000 to 2014. Since 2014 March, he has been a Professor at the Tokyo Institute of Technology. Prof. Fukawa is a senior member of IEEE. He received the Paper Award from IEICE in 1995, 2007, 2009, and 2012, the Best Paper Prize from the European Wireless Technology Conference (EuWiT), and the Achievement Award from IEICE in 2009.

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Our Research Interests

At Fukawa laboratory, we have been conducting both fundamental and applied researches involving signal processing techniques for mobile communications. Recently, we have focused on transmission systems, especially MIMO-OFDM, multiple access, modulation and demodulation schemes for cognitive radio, super high-bit rate mobile communications, and millimeter wave. Below is a detailed list of our research topics in recent five years.

Research Topics in Recent Five Years

Transmission System

MIMO detection & CSI estimation

- Suboptimal MLD
  - ✓ EM algorithm
  - ✓ Factor graph
  - ✓ MMSE detection avoiding noise enhancement
- Adaptive blind method for heterogeneous streams
- Soft decision-directed channel estimation (SDCE)
- Channel estimation exploiting sparsity

MIMO-OFDM system optimization

- BER improvement
  - ✓ Minimum BER (MBER) precoding
- PAPR reduction
  - ✓ Block diagonalization with selected mapping (BD-SLM)
  - ✓ Partial transmit sequence (PTS)
- Joint BER and PAPR improvement
  - ✓ Eigen-mode transmission with PAPR reduction
- Relaying system improvement
  - ✓ Amplify-and-Forward (AF) / Decode- and-Forward (DF) switching

Super high rate mobile communications

- 8×16 MIMO multi-Gbps systems

Multiple Access

Collision detection

Interference mitigation

- Spatial filtering
- MBER precoding for co-channel interference environment
- Neural network based power and beamforming controls
- Linear interference suppression for multiple relay systems

Access scheme

- IDMA with iterative detection
- Random packet collision solution

Wireless Security

Random phases based physical layer security

Millimeter Wave Communications

Phase noise compensation

I/Q imbalance compensation

Real zero coherent detection

Others

Constant Amplitude OFDM

Machine Learning Schemes for Wireless Communications

In this report, we will present some of the above research topics that have been recently presented at international conferences or accepted for publication in international journals.

Fukawa Laboratory

Time-Varying Channel Prediction for Pilot Contamination Mitigation in Hybrid Massive MIMO Communications [7], [10], [26], [28]

Recently, massive multiple-input multiple-output (MIMO) has attracted much attention and been introduced into the 5th generation mobile communications system (5G). Hybrid beamforming (HB), which consists of analog beam-forming (AB) and digital beamforming (DB), can be regarded as one of the most feasible massive MIMO techniques, because it can significantly reduce the number of baseband and radio frequency (RF) circuits. However, HB cannot accurately estimate channel impulse responses of all antenna elements because the degrees of freedom of the received (Rx) signal are reduced by AB and are too small for the accurate channel estimation. To solve this problem, a scheme proposed in assumes that incident angles of propagation paths (cluster) in the uplink (UL) are narrowly distributed and can estimate time-invariant channel frequency responses of all the elements from those of HB by using information on angle of arrival (AoA) for the cluster. The estimated channel frequency responses are used to control both phase rotation of AB and a precoding matrix of DB so that HB can approximately perform block diagonalization in the downlink (DL). However, hybrid massive MIMO still suffers from the following pilot contamination: When the number of user terminals (UTs) using the same channel simultaneously exceeds the number of orthogonal pilot signals, the same pilot signal needs to be shared among multiple UTs [8]. The channel estimation using the shared pilot signal obtains an estimate of combined channel frequency responses of the multiple UTs, which can cause significant degradation of transmission performance.

To cope with the pilot contamination even under time-varying channel conditions, this paper proposes to adaptively predict time-variant DL channels from UL ones while mitigating the pilot contamination. The predicted channel frequency responses are used to approximately perform block diagonalization of HB in the DL. Note that the channel estimation in assumes time-invariant (quasi-static fading) channels without any pilot contamination. Considering time division duplex (TDD) multiuser MIMO communications, the proposed scheme firstly estimates an average AoA of user's cluster by applying multiple signal classification (MUSIC) to the Rx pilot signals, which can reconstruct the channel frequency responses of the interfering UTs. Removing the reconstructed channel frequency responses from the combined ones can extract the desired channel frequency responses. Since the desired channel frequency responses can be considerably extracted, the proposed scheme coarsely compensates for time-variation of the Rx signal by predicting the Doppler effect of each cluster. The residual time-variation can be tracked and removed using detected signals of all the streams, i.e., the replica of the transmitted (Tx) signals, in a decision-directed manner. Finally, the estimated total time-variation is used to predict the DL channel frequency response. Computer simulations under conditions of time-varying fading channels, two desired UTs with multiple antennas, two interfering UTs with multiple antennas, and one base station (BS) equipped with a 256-element array antenna demonstrate that the proposed scheme can sufficiently track time-varying channels and mitigate the pilot contamination. Consider the massive MU-MIMO system shown in **Fig. 1**, where the base station (BS) and user terminals (UTs) are assumed to perform HB and full digital beamforming (FDB), respectively. Suppose that the BS with N_{RF} antennas communicates with K UTs having N_{UT} antennas. Furthermore, let us assume that K' interfering UTs are located near the cell boundary, and that $(K+K')$ UTs share the same frequency channel simultaneously. Let M_{BS} denote the number of

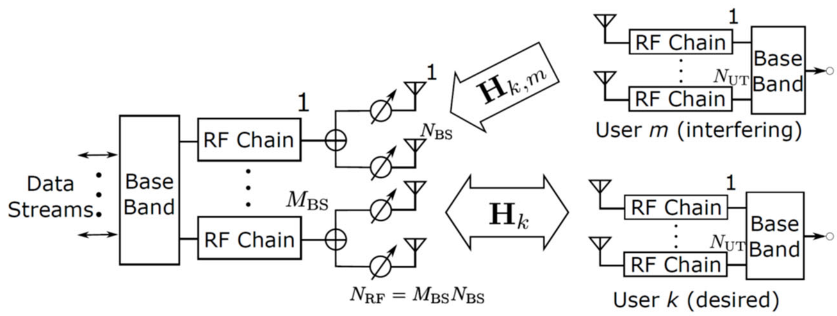


Fig. 1. Block diagram of the massive MU-MIMO system.

RF circuits (sub-arrays) in the BS and $N_{\mathrm{RF}}/M_{\mathrm{BS}} = N_{\mathrm{BS}}$ be an integer equal to the number of antenna elements per RF circuit. The number of data streams for each UT is set equal to that of antennas of each UT, N_{UT}. In addition, since a TDD system is assumed, both the uplink (UL) and DL use

the same frequency channel. Since channel frequency responses of UL agree with those of DL, the BS can control phase rotation of AB and a precoding matrix of DB for HB using estimated or predicted channel frequency responses of DL. Furthermore, since orthogonal frequency-division multiplexing (OFDM) is assumed as the transmission scheme, subcarrier signals of OFDM follow frequency flat fading even under frequency selective fading conditions. From now on, we focus on one OFDM subcarrier that experiences the Rayleigh fading.

BS and UTs were assumed to be located as shown in **Fig. 2**. The central azimuth angles of the clusters arriving from the desired UTs were set to 15° and −15°, respectively. The central azimuth angles of the clusters arriving from the interfering UTs were assumed to be uniformly distributed in the range from −75° to 75° with an angular difference from the central azimuth angle of the desired UT being 45° or more. The central elevation angles of the clusters were assumed to be normally distributed with 0° mean and standard deviation 15°. The direction of the movement of the UTs was assumed to follow the uniform distribution.

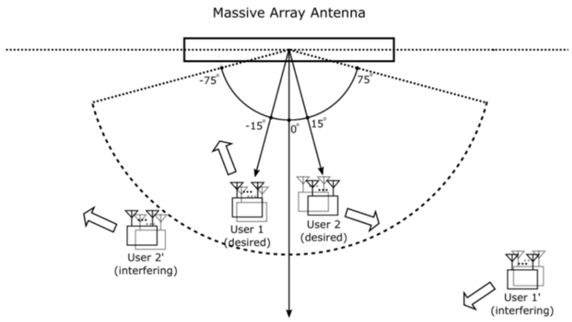


Fig. 2. The positions of BS and UTs.

Fig. 3 shows the mean squared error (MSE) of the predicted channel at the center of the DL packet. The error floor can be seen when the pilot contamination (PC) occurs but PC mitigation (PCM) is not conducted, whereas PCM can make the error floor much lower and near to that without PC. In addition, PCM can reduce differences in required E_{b}/N_0 between PC and non PC to less than 3 dB. Especially, when the channel is time-variant, the difference can get close to 0 dB. It can be also seen that the proposed scheme can accurately predict the time-varying channels up to $f_{\mathrm{D}} =$ 150 Hz.

Fig. 4 shows the average packet error rate (PER) of DL, when HB approximately performs block diagonalization by using the predicted DL channel. It can be seen that PCM can alleviate degradation of PER in the DL from PC, as effectively as that of MSE. Note that the simulation results of the second stream (the smaller eigenvalue) without PCM were not plotted because the PER is very close to 1.0 regardless of both the Doppler frequency and E_{b}/N_0. The proposed scheme estimates the average AoA of each UT's cluster and uses the information to remove channels of the interfering UTs from pilot based channel estimates. After predicting and compensating for the overall Doppler effect of each desired UT's cluster, the residual time-variation can be further tracked using the detected signals of all the Tx streams. Finally, the estimated total time-variation is exploited to predict the DL channel.

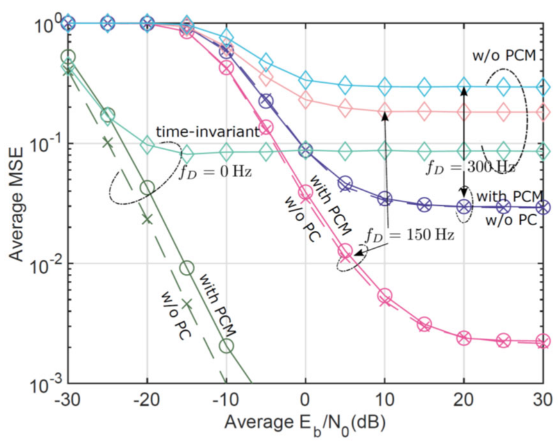


Fig. 3. MSE of channel prediction in DL.

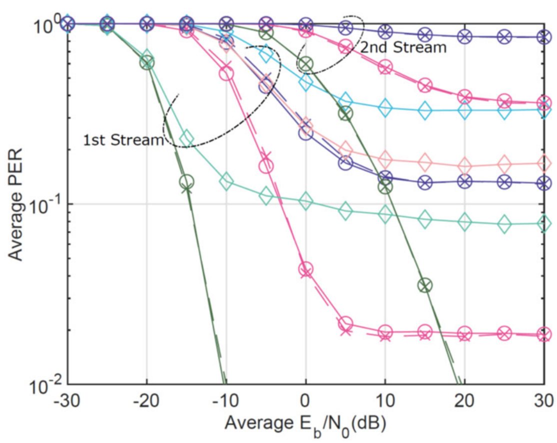


Fig. 4. Average DL PER of each stream.

Fukawa Laboratory

Random Phase based Physical Layer Security Scheme Robust against Multi-Antenna Eavesdroppers [16], [19]

In contrast with the upper-layer security, the physical-layer security for wireless communications can repel physical layer attacks such as eavesdropping control signals. As conventional physical-layer security schemes for multi-input single-output (MISO) communications, artificial noise (AN) and artificial fast fading (AFF) need high transmit power, while random phase (RP) can reduce the power drastically. This is because RP sets phases of transmit signals randomly and estimates their amplitudes that can minimize the transmit power under the constraint of correct signal detection by the legitimate user. A major problem of these schemes is that the desired signal can be intercepted by eavesdroppers (Eves) having multiple receive antennas. Thus, this work proposes an enhanced version of RP that multiplies the desired complex symbols by random patterns so that Eve with multiple antennas cannot detect the desired symbols even by employing diversity combining with blind algorithms. The above multiplication changes the statistical property of the desired symbol, which can destroy the basis of the blind estimation of the diversity combining weights and thus can hinder the blind diversity combining. Computer simulations of MISO QPSK demonstrate that the proposed scheme can prohibit Eve performing the blind diversity combining from detecting the desired symbols much more strictly than the conventional RP, while maintaining good transmission performance of the legitimate user (Bob).

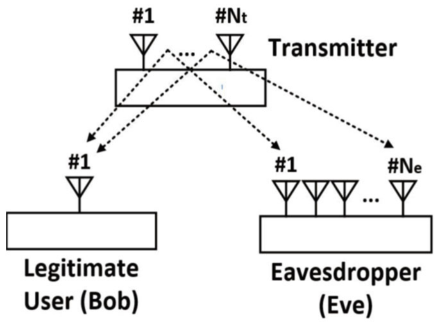


Fig. 5. System model.

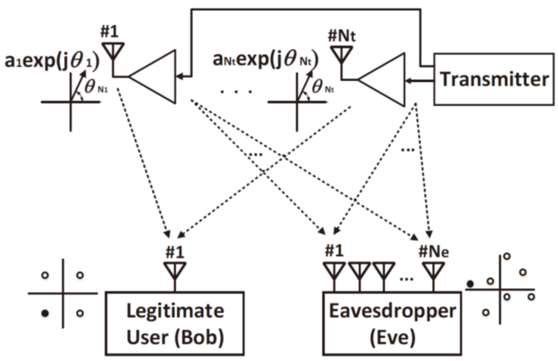


Fig. 6. Conventional RP scheme.

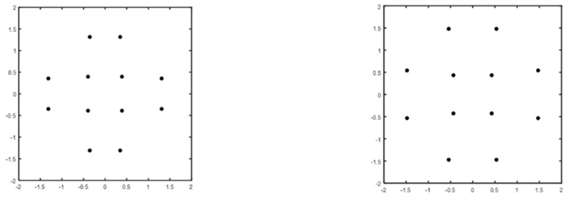
We consider a MISO system shown in **Fig. 5**, where the transmitter is equipped with N_t Tx antennas, and Eve has N_e Rx antennas with $N_\mathrm{e} \geq N_\mathrm{t}$. Because of MISO, suppose that Bob has a single Rx antenna. In addition, this time we focus on one subcarrier of orthogonal OFDM, and QPSK is assumed as the modulation scheme for the subcarrier. From now on, all signals are represented in equivalent low-pass waveforms. **Fig. 6** shows the conventional RP scheme including Eve equipped with multiple Rx antennas. In the RP scheme, a complex symbol (the desired signal) transmitted from a Tx antenna is rotated by a random phase, and then its amplitude is controlled so that the total Tx power can be minimized under the constraint that Bob should correctly receive the symbol.

When Eve has only one Rx antenna, the random phase makes it impossible for her to detect the desired signal. When Eve has multiple Rx antennas, however, she can conduct diversity combining with blind algorithms. To prohibit multi-antenna Eve from eavesdropping the desired signal, this report proposes an enhanced version of RP that multiplies the above desired signal by a random pattern. This multiplication changes the statistical property of the desired signal, which can destroy the basis of the blind estimation of the weights and thus can hinder the eavesdropping.

When QPSK is assumed as the modulation scheme of the target subcarrier, let ξ denote the random pattern and ξ is set as follows:

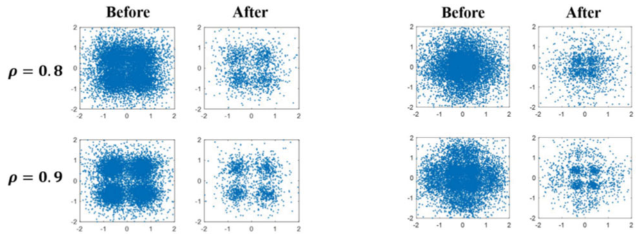
$$\xi = \begin{cases} xA & , P_1 \\ Ae^{j\phi} & , P_2, \\ Ae^{-j\phi} & , P_2 \end{cases}$$

where x and A are positive constants, ϕ denotes a phase, and P_1 and P_2 are probabilities to satisfy that $\langle \xi \rangle = 0$ and $\langle |\xi|^2 \rangle = 1$, where $\langle \ \rangle$ denotes the statistical expectation operator. After generating ξ according to the equation above, the desired signal d is replaced by ξd as: $d \longleftarrow \xi d$. **Fig. 7** shows the constellation points of ξd using some suboptimal parameters. Evidently from these figures, introducing the random pattern can increase the number of constellation points from 4 to 12 in the case of QPSK. These suboptimal parameters can enlarge the distance between the nearest neighboring constellation points compared to most of the parameter candidates, while causing severe degradation in the BER performance of Eve with multiple Rx antennas. **Fig. 8** shows outputs of the diversity combining performed by Eve in both the conventional and enhanced RP schemes, when $N_\mathrm{t} =$ 4, $N_\mathrm{e} =$ 16, and average $E_\mathrm{b}/N_0 =$ 30 dB, where ρ is the factor indicating the channel correlation between Bob and Eve. In the figure, "Before" indicates signals received by one Rx antenna while "After" indicates the diversity combining outputs after sufficient number of iterations for RLS-CMA. In the case of the conventional RP scheme, the received signals get closer to the QPSK constellation points as the channel correlation factor, ρ, increases from 0.8 to 0.9.



(a) $\phi = 120^\circ, P_1 = 0.55$ **(b)** $\phi = 155^\circ, P_1 = 0.70$

Fig. 7. Examples of constellations (QPSK).



(a) Conv. RP. **(b) Enhanced RP.**

Fig. 8. Outputs of the diversity combining in Eve.

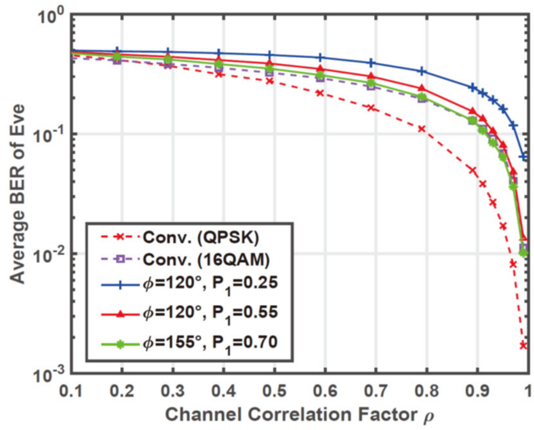


Fig. 9. BER performance of Eve.

It can be seen that by employing the diversity combining with RLS-CMA, Eve can detect the QPSK symbol with higher reliability. In the enhanced RP scheme, Eve cannot correctly receive all the constellation points even when she performs the diversity combining with RLS-CMA. Specifically, Eve can barely observe 4 constellation points located near the center but cannot detect the other points. This is because the random patterns are generated according to their different probabilities. Note that the above situation of Eve means that the bit error rate (BER) performance is severely degraded even when the diversity combining with RLS-CMA is employed, which can be seen from the simulation results about BER. **Fig. 9** shows the average BER performance of Eve. In the conventional RP scheme, the BER of Eve is improved with an increase in the number of Rx antennas, when ρ ranges from 0.9 to 1.0. This is because increasing the number of Rx antennas can gain more diversity effect and improve the BER. In the enhanced RP scheme, however, the improvement of the BER is very limited because the enhanced version violates the basic assumption of the blind algorithms and thus can hinder even RLS-CMA.

Fukawa Laboratory

Device-to-Device Communications Employing Fog Nodes with Parallel Interference Cancellers [15], [20]

Device-to-device (D2D) communication allows user terminals to directly communicate with each other without the need for any BSs. Since the D2D communication underlying a cellular system shares frequency channels with BSs, co-channel interference may occur. Successive interference cancellation (SIC), which detects and subtracts user signals from received signals in descending order of received power, can cope with the above interference and has already been applied to fog nodes that manage communications among machine-to-machine (M2M) devices besides direct communications with BSs. When differences among received power levels of user signals are negligible, however, SIC cannot work well and thus causes degradation in BER performance. To solve such a problem, this work proposes to apply parallel interference cancellation (PIC), which can simultaneously detect both desired and interfering signals under the maximum likelihood criterion and can outperform SIC irrespective of channel conditions even when power level differences among users are small.

The fog node, which is located near D2D user elements (DUEs), operates as an interface between BS and DUEs. In addition, the fog node can be regarded as a smaller scale cloud server and provides DUEs with additional computing capabilities. Data of DUEs are sent to not BS but the fog node that can conduct data computing, storage, and processing, which can increase network reliability and protect core networks. Furthermore, it can discover the D2D pairs, store information, schedule the resource block (RB), control the transmit power of the D2D devices, continuously monitor the D2D environment, and perform channel estimation. Note that fog node employing SIC can improve energy efficiency of D2D communications. Under some channel conditions, SIC with channel decoding can be superior to PIC with channel decoding in terms of BER performance. From SIC and PIC, adaptive interference cancellation (AIC) selects one canceller that can yield better BER performance.

This work considers both simple and complex system models. In the simple model of **Fig. 10**, one DUE communicates with another DUE via one fog node and shares one channel with one cellular user element (CUE). Let us assume that the fog node can perfectly estimate its relevant channels and carries out functions of SIC, PIC, or AIC. In the complex system model, a number of DUEs are connected to fog nodes and a number of CUEs are supposed to be distributed in a cell. Let us assume a fully loaded network in which each CUE uses two RBs to communicate with one BS. DUEs are assumed to share RBs with CUEs and to generate data packets following a Poisson process.

It can be seen from **Fig. 11** that these two curves intersect with each other when E_b/N_0 = 12.5 dB and power ratio (PR) = 0.6. This means that when the channel coding is employed, SIC can outperform PIC under low SNR conditions. **Fig. 12** shows two-dimensional areas (E_b/N_0, PR) where SIC or PIC is superior to the other in terms of average BER, with R = 1/2.

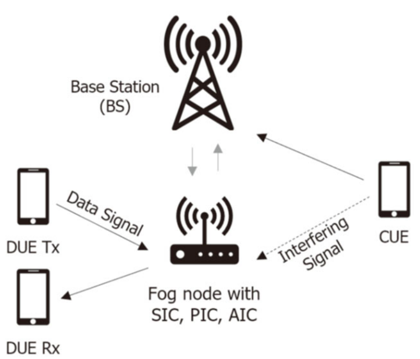


Fig. 10. System model.

SIC and PIC can provide better average BER performance of both the strong and weak users, in the horizontally and diagonally hatched areas of **Fig. 12**, respectively. In the vertically hatched region, PIC is superior when the DUE signal has higher received power than that of the interfering signal whereas SIC is superior when the DUE signal has lower received power than that of the interfering signal. In general, when the received power difference is small, PIC outperforms SIC. On the other hand, when the difference is very large, SIC can show better BER performance than PIC under some channel conditions.

Since DUE senders are expected to exceed available RBs in the number, the fog node should schedule packet transmission of DUEs on the basis of their waiting time, data size, and so on. The highest priority DUE is supposed to select the RB that can maximize its throughput. Since one CUE shares the selected RB, the lower priority DUEs are not allowed to pair up with the CUE and should select the best one from the other available RBs. When the selected RB cannot satisfy the requirement of BER, the DUEs have to wait until suitable RBs become available, which makes the transmission delay time longer. **Fig. 13** shows the average throughputs, where no interference cancellation (NIC) case assumes that one DUE directly communicates with another DUE without any fog nodes. It can be seen, PIC and AIC achieve the almost constant gain of 10% over SIC irrespective of the transmit power of DUE. This implies that PIC has a larger dominant region than that of SIC and that selecting proper code rate can increase the average throughput more drastically than SIC. As for NIC, its throughput is the worst because it cannot cancel any interfering signals. **Fig. 14** shows the cumulative distribution functions (CDFs) of delay times. Since NIC does not use any fog nodes, its transmission delay time can be less than 1 ms. For interference cancellers employing the fog nodes, their transmission delay time must exceed the sub frame length of 1 ms, which can be regarded as a bottleneck. Even though NIC does not suffer from such a bottleneck, many DUEs cannot pair up with suitable CUEs in sharing RBs, which increases the transmission delay time of NIC. It can be seen from the figure that plots of AIC and PIC overlap, which implies that PIC showed better BER performance than SIC. Further, PIC can make the transmission delay time shorter than SIC. In addition, PIC can increase times of successful packet transmissions more than SIC.

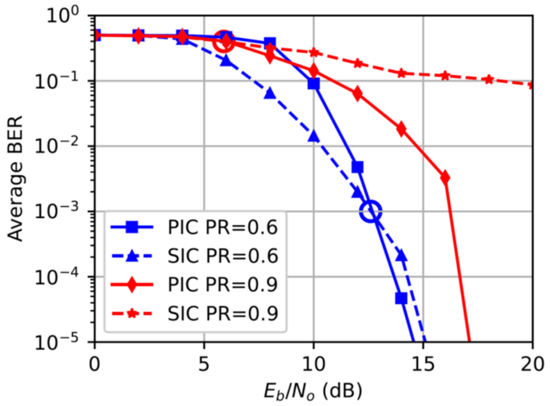


Fig. 11. Average BER for weak user.

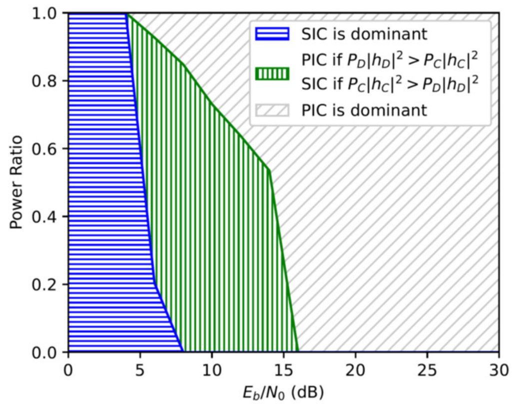


Fig. 12. Dominant Regions (R = 1/2).

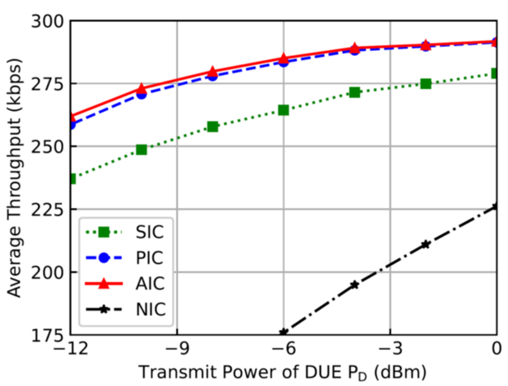


Fig. 13. An example of average throughput.

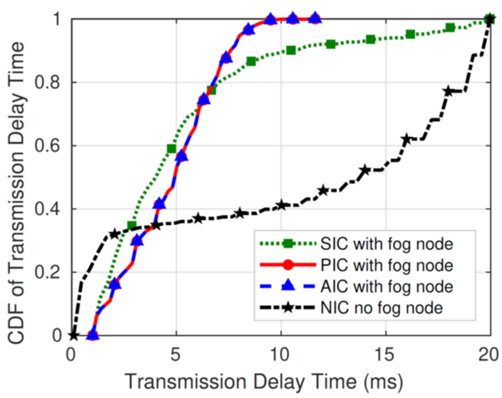


Fig. 14. Transmission delay time.

Nishikata Laboratory

Home page: http://www.ns.ee.e.titech.ac.jp/

Associate Professor Atsuhiro Nishikata

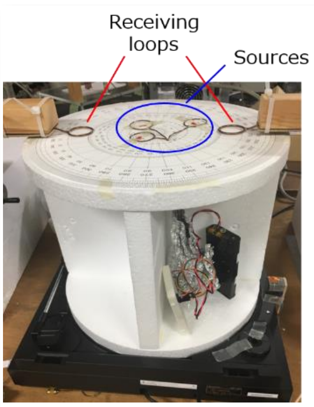
Assoc. Prof. Atsuhiro Nishikata was born in 1961, Tokyo, Japan. He received his B.S. degree in physics, M.E. and D.E. degrees in electrical and electronic engineering, all from Tokyo Institute of Technology in 1984, 1986 and 1989, respectively. From 1989 to 1993, he was a Researcher at EMC (Electromagnetic Compatibility) Group in Communications Research Laboratory; CRL (predecessor of National Institute of Information and Communications Tecchnology; NICT). From 1993 to 1995, he was a Research Associate at Tokyo Institute of Technology, where he has been an Associate Professor since 1995. He was also a part time researcher at NICT from 2004 to 2008. His current research interests are the EM noise identification and suppression, magnetic shielding, RF material measurement, RF interaction with human body, sound source localization, retroreflector and its application to detection and communication. He is a member of IEICE, IEEJ and IEEE, vice chair(2019.6-2021.6), char(2021.6-2023.6) of IEICE Technical Committee on Electromagnetic Cmopatibility (EMC).

Recent Research Topics

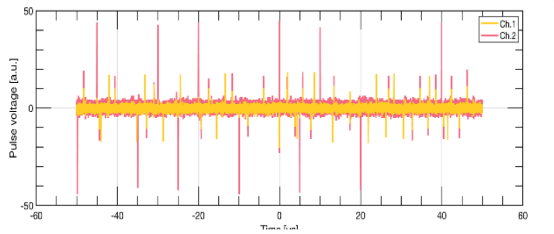
- **Full-Duplex Communication Experiment by BPSK-modulated Retroreflector**
- **Analysis for Scattering Directivity of Retroreflector Having Inter-Element Coupling**
- **Impulsive Magnetic Source Localization by Two Loop Antennas and a Turntable**
- **Nondestructive ε_r and μ_r Measurement Using Circular TE01 Mode Waveguide Ends**
- **Physical and Mechanical Modelling of Ferromagnetic Materials' B-H Characteristics**

Multiple Impulsive Magnetic Noise Source Localization by Using Two Loop Antennas and a Turntable

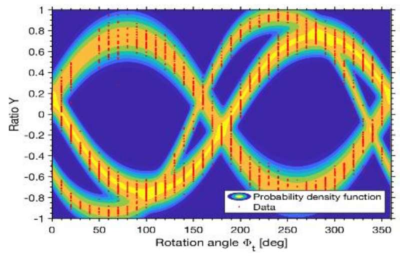
Supposing the electromagnetic noise radiation generated from digital circuits or switching power supplies, we proposed a method for estimating the source position of impulsive magnetic noise using a simple equipment. The measurement system consists of two receiving loop antennas fixed in the horizontal plane and a turntable. As each noise source, the vertical magnetic dipole moment was fixed on a turntable. The two receiving antennas were fixed so that their center points were 100 mm to the left or right of the center of rotation. The noise waveforms were simultaneously recorded by two loop antennas while the turntable was rotating, and a pair of peak voltages V1 and V2 was obtained for each impulse noise. When the voltage ratio Y = (V1 − V2)/(V1 + V2) is plotted against the rotation angle, it agrees well with the theoretical probability density function that has the wave source position



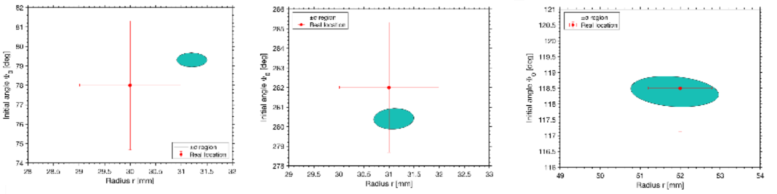
Experiment setup



Recorded noise waveform



Y vs rotation angle and PDF


Estimated positions of noise sources

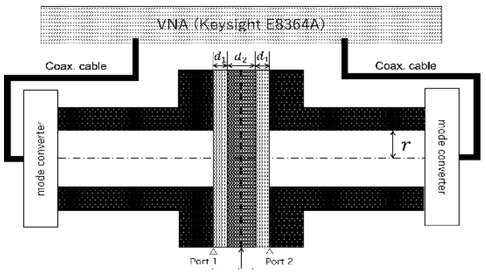
as parameters. By maximum likelihood estimation, the positions of the three wave sources are simultaneously estimated as the polar coordinate's radius and angle, within the accuracy of 1 mm and 2 degrees, respectively.

Electrical Constant Measurement of Soft Materials Put Between Two Circular TE_{01} Mode Waveguide Open Ends

Measuring the electrical constants ($\varepsilon_r = \varepsilon_r' - j\varepsilon_r'', \mu_r = \mu_r' - j\mu_r''$) of materials including biological substances is very important for EMC analysis. The coaxial open-end probe method has been widely used to nondestructively measure the permittivities of solids, as well as semi-solids or liquids. However, the coaxial probe method is highly influenced by the air gap between MUT (Material Under Test) and the probe. For this problem, we have been investigating the waveguide open-end probe method that utilizes circular TE_{01} mode where no normal E-field component exists on the conductor surface and the measurement is less influenced by the air gap. The method has been extended to measure not only ε_r but also μ_r. Now the method is enabled to measure soft and unshaped MUT.

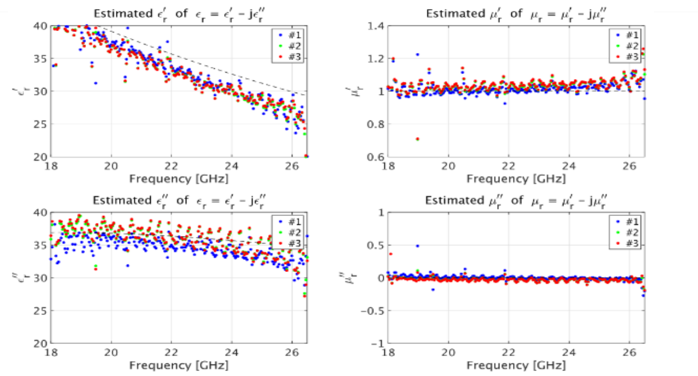

Two port measurement setup

To measure soft MUTs that easily deforms, MUTs are sandwiched between two sheets of glasses with thickness $d_1 = 0.342$ mm. Experimental setup with r=11.9 mm works on K-band (18 ~ 26.5 GHz). Electrical constants of glasses $(\varepsilon_{r1}, \mu_{r1})$ are measured beforehand, then those of MUT (ε_r, μ_r) are estimated by equating theoretical S-parameters with measured ones. To derive theoretical S-parameters, it is reduced to one-port problem with assuming the magnetic wall or the electric wall at the virtual plane placed at the center of the thickness d_2. From the measured S-parameters, ε_r and μ_r are inversely determined by the help of two-dimendional Newton-Raphson method.



Schematic expression of system

MUT (deionized water solidified with agar, d_2=1.064 mm, T=23.5℃) was measured three times. Resulting ε_r was consistent with Kaatze's formula shown by dashed line curves, and μ_r of almost unity is obtained as it should be.



Measured result of H_2O solidified with agar

Fujii and Omote Laboratory

Specially Appointed Professor Teruya Fujii

He received the B.E. degree from Kyushu Institute of Technology in 1981 and M.S. and Ph.D. degrees from Kyushu University in 1983 and 1995, respectively. In 1983, he joined NTT Yokosuka Lab. He involved in R&D activities of mobile communications and mobile radio propagations. In 2000, he moved to Japan Telecom (Softbank Corp.). After he successfully completed his Softbank R&D department head term, he became the first R&D fellow of Softbank in 2016. In 2017, he became a specially appointed professor of Tokyo Institute of Technology as an additional position.

Specially Appointed Associate Professor Hideki Omote

He received his B.S. and M.S. degrees from the University of Nagoya, Japan, in 1997 and 1999, respectively. He joined Japan Telecom Co, LTD. (currently, Softbank Corp.) in 1999. Since then, he has been engaged in the research of radio propagation for mobile communication systems. He also has been engaged in the standardization of radio propagation for mobile communication in ITU-R SG3. He is currently managing Antenna and Propagation Section of Research and Development Division at Softbank Corp. In 2017, he also joined Tokyo Institute of Technology, where he researches radio propagation and modeling. He is a member of IEICE.

Recent Research Topics

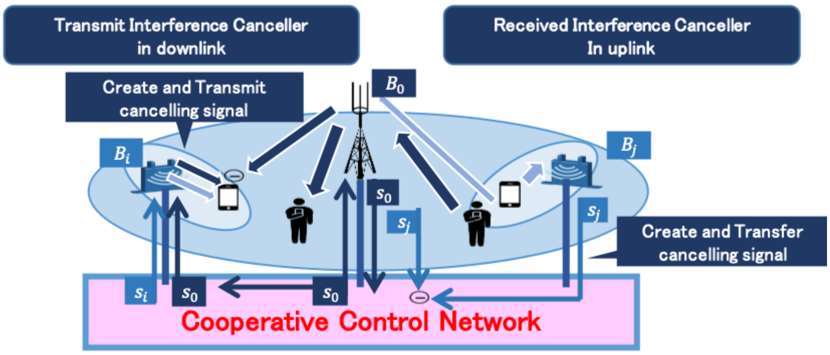
- **3D Layered Cell Construction in Broadband Mobile Communication**
  - Transmit and Receive Interference Canceller for 3D Layered Cell Construction in Broadband Mobile Communication.
  - Frequency Sharing in 3D Cell Structure consisting of Ground and Sky Cells by using Beamforming.

A Study on Transmit and Receive Interference Canceller for 3D Layered Cell Construction in Broadband Mobile Communication

[1][3]~[5][7][9][10][13][15][17][19]~[21]

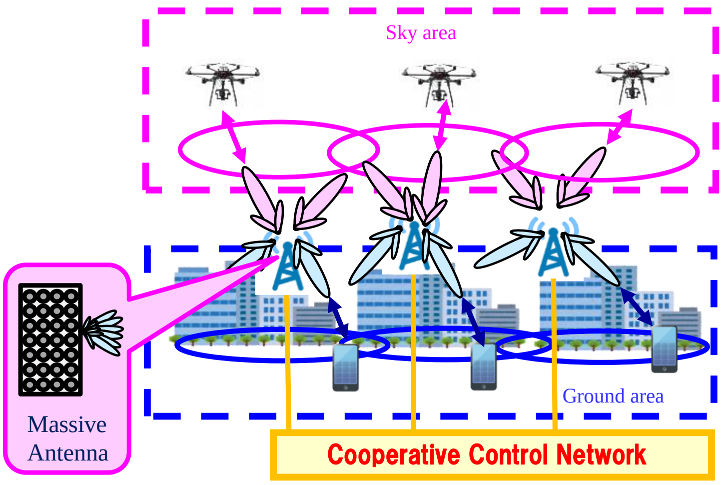
In the three-dimensional(3D) layered cell construction in same frequency bands are used in both macro and small cells, we pioneered interference cancellation technology using "cooperation control network" where each cell cooperates through a network ahead, for LTE and 5th generation mobile communications. We propose "transmit interference canceller in small cells extended to MIMO and SIMO" that cancels the macro cell signal received at terminal in each small cell through cooperative control network in downlink and "received interference canceller in macro cell" that cancels the small cell signal received at base station in macro cell through cooperative control network in uplink.

By using these proposed interference cancellers, we showed that the communication quality such as SINR (Signal power to Noise and Interference power Ratio) and communication capacity in small cells can be improved remarkably.



A Study on Frequency Sharing in 3D Cell Structure consisting of Ground and Sky Cells by using Beamforming [2][6][8][11][12][14][16][18][22]

It is being expected to control the flight of drones and transmit video data taken with drones using cellular network. When the mobile terminal on the drone communicates in the sky using current cellular network, it interferes with a wide range and the radio quality of the mobile terminals on the ground is deteriorated. We proposed "3D Cell Structure" which shares the same frequency by spatially separating the ground cell and sky cell by using 5G antenna beamforming for the base station antenna. We evaluate the communication characteristics when mobile terminal on the drone communicates in a conventional cellular system and evaluate its effectiveness in comparison with the proposed system. We are working on the optimization design of "Massive Antennas" that take into account the arrival angular spread, and on the modeling of the fading characteristic of radio waves in the sky, which is indispensable for wireless communications.



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