Mobile Communications Research Group
Tokyo Institute of Technology

2020
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.

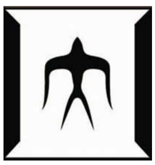
Mission

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 4 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. Kentaro Saito, and
  Specially Appointed Assoc. Prof. (Lect.) Azril Haniz
- 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 (Device Lab.):
  Prof. Kenichi Okada and Assist. 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

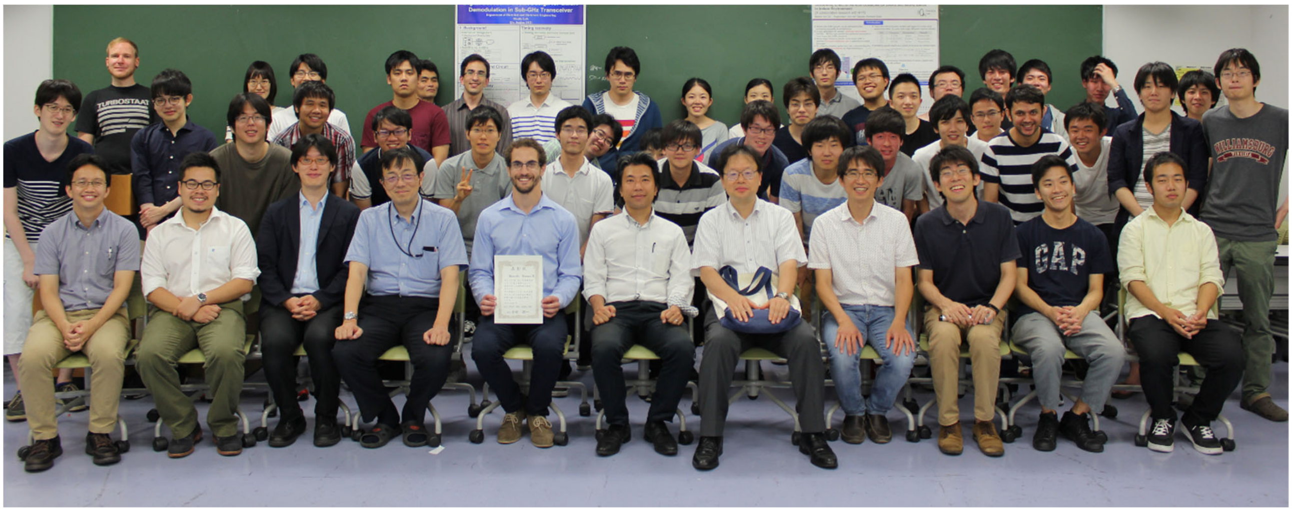
Beside the general research activities, for encouraging closer cooperation within MCRG and with the external companies, institutes and organizations, “Open House” and “Future Communication Research Workshop” are holed regularly. In addition, irregular invited speeches and lectures are also hold to broaden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

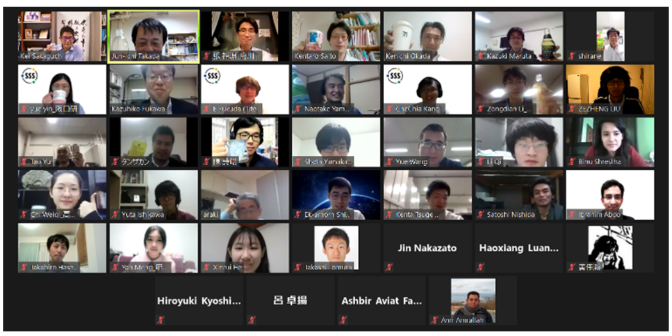
Future Communication Research Workshop

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 and senior member of IEEE. He is serving as a vice president of Japan Society for International Development (JASID).

Assistant Professor Kentaro Saito

Assistant Professor Kentaro Saito was born in Kanagawa, Japan, in 1977. He received his B.S. and Ph.D. degrees from the University of Tokyo, Japan, in 2002 and 2008, respectively. He joined NTT DOCOMO, Kanagawa, Japan, in 2002. Since then, he has been engaged in the research of IP networks, transport technologies, MAC technologies, and radio propagation for mobile communication systems. He has been engaged in the development of the LTE base station. He joined Tokyo Institute of Technology, Japan, in 2015. Since then, he has been engaged in research of radio propagation measurements and MIMO channel modeling. He received the best paper award of IEICE SRW conference in 2017, the IEICE Best Tutorial Paper Award in 2019, and the best letter award of IEICE ComEX in 2020. He is a senior member of IEICE and a member of IEEE.

Postdoctoral Researcher Panawit Hanpinitsak

Panawit Hanpinitsak was born in 1991, Khonkaen, Thailand. He received the B.E. degree (Hons.) from Sirindhorn International Institute of Technology, Thammasat University, Thailand, in 2013, and the M.E. and D.E. degrees from Tokyo Institute of Technology, Japan, in 2016 and 2019, respectively. His research interests include radio propagation channel modeling and dynamic spectrum sharing at millimeter waves. He was a guest PhD researcher at Aalborg University, Denmark in 2016, and Ilmenau University of Technology, Germany in 2018. He received best student presentation award of IEICE SRW conference in 2017, and best student paper award from IEEE APS in 2019. He is a member of IEICE and IEEE.

Postdoctoral Researcher Nopphon Keerativoranan

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 localization and tracking, Cyber-physical system, and measurements for wireless communication system and application. He is a member of 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 millimeter-wave radio channel modeling for the Beyond-5G system and the millimeter-wave band dynamic spectrum sharing system. We also investigated the radio propagation model for a variety of scenarios such as underground railways, Internet of Things (IoT) systems, and the rain attenuation in tropical regions. We are also developing the technologies that detect and measure the radio signals of the commercial wireless systems to understand the radio propagation characteristics in real environments. Another research topic is the establishment of radio propagation simulation techniques. The recent issues are the physical optics approach combining geometrical optics and Uniform theory of diffraction. We also studied the environment model construction techniques from camera images and laser scanners for those propagation simulation researches. The individual topics are as follows.

Recent Research Topics

- **Radio Spectrum Sharing Research**
  - Location, Orientation, Power and Antenna Pattern Estimation for Spectrum Sharing at High-Frequency Bands
  - Clarification of the Propagation Mechanisms of FWA system in 26 GHz Band Toward Spectrum Sharing with 5G
  - Channel Measurement System Using SDR-based Receiver and Cellular Signal
- **Radio Propagation Simulation and Environment Modeling Research**
  - Under-sampling Interpolation of the Wireless Channel Impulse Response Using Extended Kalman Filter
  - Object Shadowing Detection Method by Stereo Vision for Wireless Channel Simulation in Dynamic Environment
  - Visualization Tool of the Urban Microcell Radio Propagation Paths
  - A Novel Mirror Kirchhoff Approximation for Predicting Shadowing
  - A Computational Cost Reducing Technique for Physical Optics Based Propagation Channel Simulator at mm-Wave Bands
- **Radio Propagation Research**
  - A Study for Propagation Estimation near Concrete Ceiling at 920MHz
  - Study on Frequency Characteristics in Outdoor Street Canyon Scenario at mm-Wave Bands
  - Comparison of Complex Permittivity Measurement Methods for Radio Propagation Simulation
  - On the Modeling of Cylindrical Objects in the Radio Propagation Prediction

Takada Laboratory

Location, Orientation, Power and Antenna Pattern Estimation for Spectrum Sharing at High-Frequency Bands

(Supported by the Ministry of Internal Affairs and Communications JPJ000254)

Because of the shortage of spectrum caused by the rapid increase of wireless applications, the fifth generation (5G) system at 28 GHz band will be deployed. However, this band has already been allocated by the existing fixed system. Thus, to prevent the interference, the coverage area of the fixed system has to be estimated. However, sometimes the position, orientation, power, and antenna pattern information of the fixed system are not available in the temporary or mobile system, because they are not recorded in the database. Since these parameters are required for coverage range calculation, they have to be estimated first.

Table 1 Parameter Estimation Results

	Proposed	Conventional
Height error	25.55 m	133.97 m
Horizontal distance error	7.04 m	7.48 m
Azimuth error	2.08 deg	NA
Elevation error	1.85 deg	NA
Power error	1.57 dB	NA

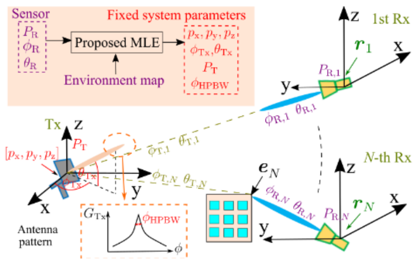


Fig. 1 Parameter Estimation Concept

Thus, as shown in Fig. 1, the maximum-likelihood (ML) based estimator is proposed based on simultaneously minimizing the azimuth of arrival, elevation of arrival, and received power errors of the sensors with the help of the map database. The proposed method was compared to the conventional method by applying to the measurement data in the sub-urban environment in Kanto, Japan. The results in Table 1 implied that the proposed method improved the positioning accuracy of the conventional method in the vertical direction. Moreover, the orientation and power prediction accuracy were decent with less than 2.08 degree and 1.57 dB error.

Clarification of the Propagation Mechanisms of FWA system in 26 GHz Band Toward Spectrum Sharing with 5G

(Supported by the Ministry of Internal Affairs and Communications JPJ000254)

The presence of the primarily-fixed stations systems, such as a fixed wireless access (FWA), is one of key challenges when using mmWave bands. To determine a sharable area among 5G and FWA, an interference level must be predicted using a propagation model. A fully-deterministic model, such as ray launching (RL) method, is often utilized for a path loss calculation. In RL, however, rays that consist of multiple diffractions are not well-defined, since they were shot discretely with a limited number of diffractions.

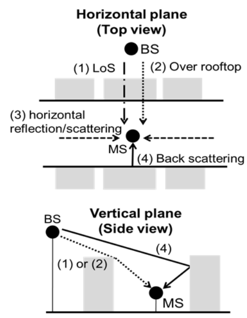


Fig.1 Categorization of path types

To solve this problem, one of the key ideas is to utilize multiple diffraction models that focus on an over-rooftop path as depicted in Fig. 1. Thus, the prominent propagation mechanism of the FWA system in a sub-urban environment was analyzed to verify the applicability of the model for the interference study between 5G and FWA. The result depicted in Fig. 2 shows that line-of-sight, over-rooftop, and back-scattering paths on a vertical plane contributed more than 90% of the power averaged for all receiver points. This implied that a combination of the traditional multiple diffraction models and back-scattering is adequate for this interference study.

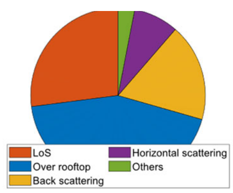


Fig.2 Power contributions averaged for all receiver points.

Under-sampling Interpolation of the Wireless Channel Impulse Response Using Extended Kalman Filter

(Supported by the Ministry of Internal Affairs and Communications JPJ000254)

Realistic channel model is essential for designing a wireless communication system. In dynamic environment, multipath fading and Doppler shift is continuously causing the change of channel characteristic in, which is manifested as a time-variant channel impulse response (CIR). However, obtaining such dynamic behavior is challenging from the measurement because only a coarse-grained CIR samples can be spatially captured.

In this work, the proposed interpolation technique based on the extended Kalman filter (EKF) was utilized to reconstruct the continuous CIR. The goal is to investigate a feasibility of the interpolation with an under-sampling condition between measured CIR. While the interpolation was successful with an oversampling condition, it cannot deterministically reconstruct CIR profile as seen in Fig. 1. However, it could successfully track some tones and range of Doppler frequency spectrum as depicted in Fig. 2.

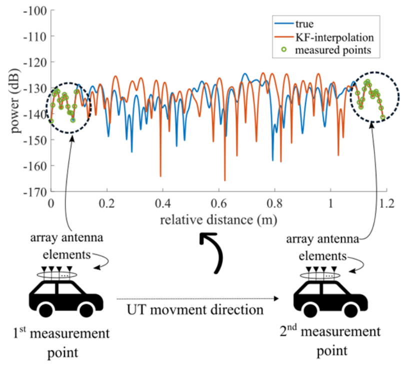


Fig. 1 interpolation scenario and results

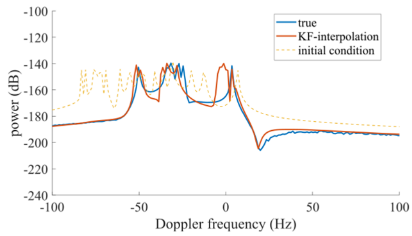


Fig. 2 Doppler power spectrum

Object Shadowing Detection Method by Stereo Vision for Wireless Channel Simulation in Dynamic Environment

(Supported by the Ministry of Internal Affairs and Communications JPJ000254)

Dynamic channel modeling has recently been gaining more attentions because of the rapid development of applications in a highly dynamic environment, e.g., an intelligent transportation system. A 3D model of moving object, e.g., pedestrian and vehicle, is necessary for the deterministic channel modeling such as raytracing method. Therefore, the dynamic 3D model detection technique by using stereo vision has been developed in this work.

Fig. 1 measurement scenario

A simple shadowing events detection based on the point clouds (PCs) obtained from stereo cameras was developed. As shown in Fig. 1, the cameras were configured to observe area around a line-of-sight (LoS) path. Depending on the PCs density along the LoS, shadowing events were identified. By cross-referencing with the measured signal power profile as shown in Fig. 2, the proposed detection method correctly identified some shadowing event. Instead of PCs, the next approach is to detect the object models from the stereo images directly to fully simulate the dynamic channel by raytracing method.

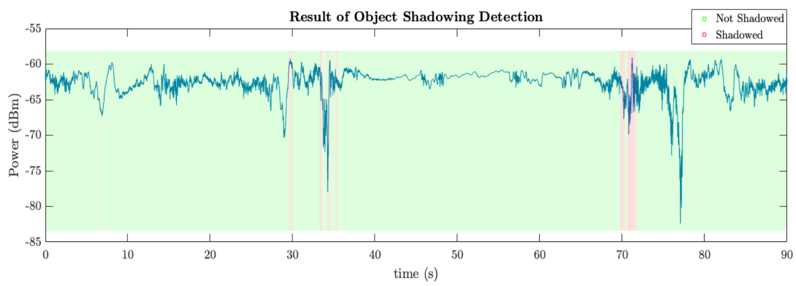


Fig. 2 Detection result on received signal power

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Visualization Tool of the Urban Microcell Radio Propagation Paths

A design of the cell site tends to be more specific toward higher carrier frequency, since various objects in the environment become electrically large. Ray-tracing-based prediction of the propagation channel has been widely utilized, in the conventional ultra-high frequency (UHF) band, by considering the simplified building structure. At a higher frequency, more detailed structures of the environment such as surface irregularity and small objects are not negligible in terms of a radio wave scattering. Recently, point cloud data captured by the use of laser scanners has been widely used in many applications. In order to acquire the details of the environment, an introduction of the point cloud data has been found useful. Point cloud data, provided by mobile mapping systems, can cover large areas and contain more details. Our objective is to implement a tool for a visual inspection of the small interacting objects for the radio propagation in an urban environment, by utilizing 3D point clouds data of a townscape and double-directional channel sounding results.

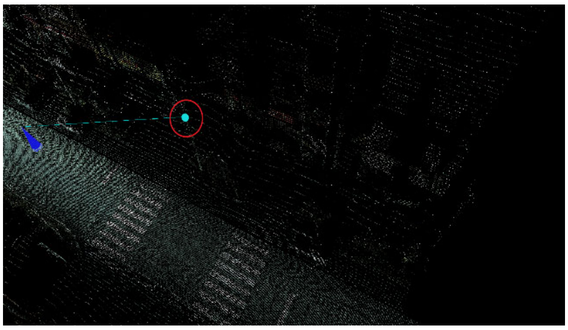


Fig. 1 Lamppost identified in the visual inspection tool

A Study for Propagation Estimation near Concrete Ceiling at 920MHz

IoT devices such as lighting system are often installed near a ceiling. For a stable link, it is important to understand the radio propagation characteristics of the environment where the equipment is used. It is assumed that the characteristic varies depending on a type of construction material. However, the propagation mechanism near the ceiling and an effective analysis method have not been clarified.

In this study, we clarify the propagation mechanism and investigate the accurate method of propagation estimation. We use two different methods, ray tracing (RT) and FDTD, to clarify the mechanism and validate the effectiveness of the method by comparing with measurement results. A flat concrete ceiling model, commonly used in factories and warehouses, was assumed as shown Fig. 1. In Fig. 2, it was found that the FDTD method was coincided with the measurement results, while the RT results have an accuracy error of 10 dB at 30-m distance. This difference is considered to be due to the fact that the FDTD method can analyze the propagation in the concrete and on its surface, while the RT method cannot. The effectiveness of the FDTD method was confirmed for the estimation of the propagation near the ceiling, whereas it is difficult to estimate by using the RT method.

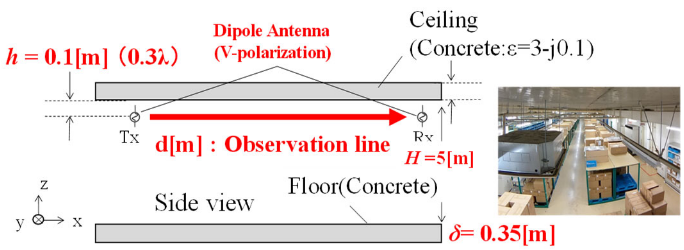


Fig. 1 Concrete ceiling model (warehouse)

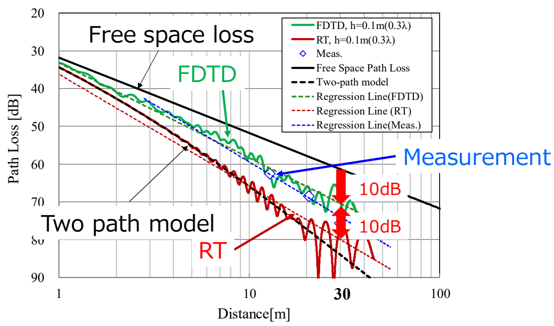


Fig. 2 Simulation and measurement results

Study on Frequency Characteristics in Outdoor Street Canyon Scenario at mm-Wave Bands

Recently, the demand for higher data rate communication has drastically increased. Since the communication system at low frequency bands (< 6 GHz) is congested, it is necessary to move toward millimeter wave (mmWave) band, especially in the 5G system, which can provide a larger bandwidth. Although mmWave has a benefit from a higher data rate, coverage range is limited due to a higher path loss. Hence, a study of frequency-dependent mmWave channel is necessary to determine the most suitable frequency band. Diffuse scattering is one of the propagation mechanisms that occurs when a radio wave is incident on a rough or uneven surface. At the mmWave band, since surface roughness can be comparable with the wavelength, diffuse scattering becomes more dominant, which cannot be ignored.

The goal of this work is to clarify the frequency-dependent channel characteristic at the mmWave bands in a street canyon scenario. This research proposed the use of physical optics (PO) simulation with a point cloud data to predict and compare the diffused scattering clusters at 30 and 60 GHz. As shown in Fig. 1, point clouds, containing surface information, was measured by a laser scanner. The predicted clusters of diffused scattering will be validated with the measurement results

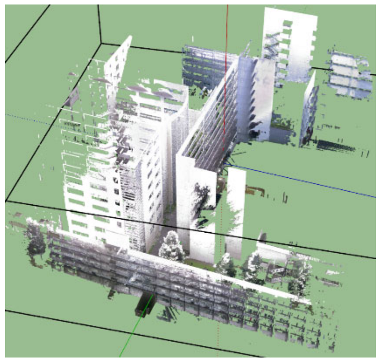


Fig. 1 Point clouds information

Channel Measurement System Using SDR-based Receiver and Cellular Signal

The most used way of channel measurement using channel sounders requires a radio license of the desired frequency band for the measurement purpose. However, it is not easy to get the radio license because of a congestion of the frequency in microwave bands and the process is tedious. One of alternative ways of the channel measurement is using a commercial signal.

This work considers the use of cellular signal and software-defined radio receivers for a channel measurement. Mobile router operating in a cellular network was used as a transmitter (UE) and USRP-based receivers were used as receivers. To monitor a power of the cellular signal, the correlation receiver system was calculated between one reference receiver (Rx_r), which was kept near UE, and the actual receiver (Rx_2), for the channel measurement as shown in Fig. 1. Measurement system verification was done in the setup as shown in Fig 2. The purpose of this measurement is to examine a channel gain measurement using the correlation receiver consisting of USRPs in a two-path case. the WCDMA uplink signal was transmitted using a mobile router and was received by the antenna located at 2-m distance away from UE. While path loss of a 20.1-m cable was estimated to be 9.3 dB when using the correlation receiver, it was 8.1 dB when measured using a signal generator and spectrum analyzer. This measurement system will be used in the outdoor point-to-point channel measurement.

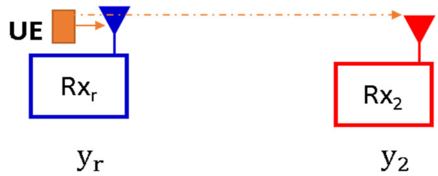


Fig 1. Channel measurement concept

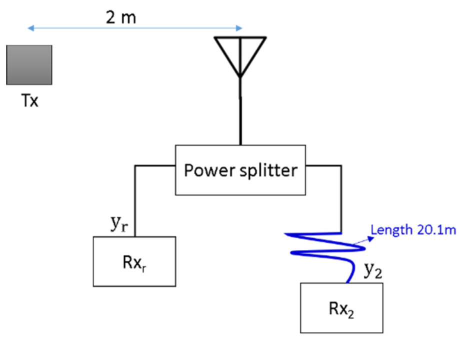


Fig 2. Measurement setup

Takada Laboratory

A Novel Mirror Kirchhoff Approximation for Predicting Shadowing

At millimeter wave (mmWave), shadowing effects greatly impact a cellphone link performance. Conventionally, full-wave electromagnetism approaches, such as method of moment (MoM), are widely used for an estimation of those effects. However, the calculation cost of MoM is a significant issue, especially at mmWave bands. Therefore, Kirchhoff approximation (KA) approach is an effective candidate for the simulation in those frequency bands. However, the conventional KA has the accuracy issue in predicting the shadowing effect from a thick object. This research proposed an efficient and accurate prediction method based on KA, called "mirror Kirchhoff approximation" (MKA), for calculating the shadowing gain by a metal cuboid.

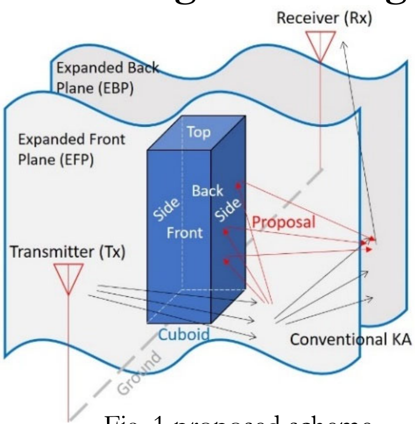


Fig. 1 proposed scheme.

The proposed MKA was validated by comparing with MoM and KA in terms of accuracy and calculation time. Comparing with the conventional KA, the MKA had a maximum of 8.3 dB improvement. Comparing with MoM, the calculation time of MKA was improved by 392-915 times. The results implied that the proposed method presented a good accuracy with a low calculation time.

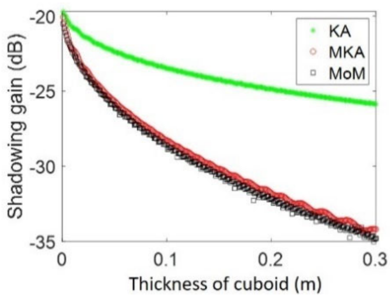


Fig. 2 prediction results.

A Computational Cost Reducing Technique for Physical Optics Based Propagation Channel Simulator at mm-Wave Bands

(Supported by the Ministry of Internal Affairs and Communications SCOPE 185103006)

In millimeter wave (mmWave) communication system, a coverage of each base station is mainly defined by a scattering channel for it has more potential to reach the mobile station. Conventionally, physical optics (PO) method is a better numerical tool for the scattered field prediction than a ray-tracing method, because PO considers field elements integration from the secondary sources on the illuminated surfaces, rather than only the specular reflection used in the ray-tracing. However, computational cost proportion to frequency becomes intolerable in mmWave band. The computational cost reduction technique for PO-based propagation channel simulator was proposed. The technique constraints an integration area of point cloud near a stationary phase point (SPP), because integrating elements far from SPPs areas are cancelling one another. As the result, the computational cost of the proposed method depends only on the number of SPPs instead of the entire area of the scatterer. In the measurement, uniformly distributed point cloud was obtained using a laser scanner. The predicted scattering channel of the proposal has been confirmed since a comparison with those computed by the conventional PO showed a strong agreement in terms of a beamforming-based angular power spectrum.

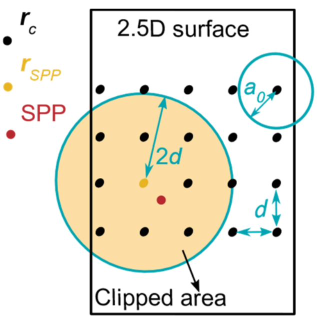


Fig.1 SPP-near coordinate searching algorithm.

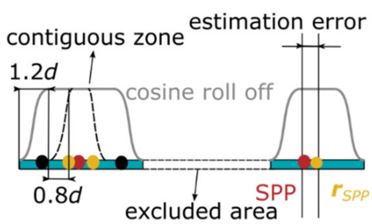


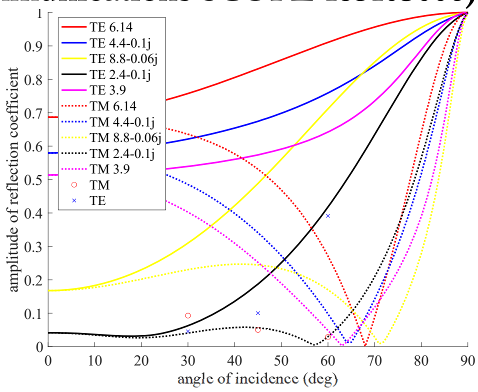
Fig. 2 Weight function for PO calculation on clipped surface.

Comparison of Complex Permittivity Measurement Methods for Radio Propagation Simulation

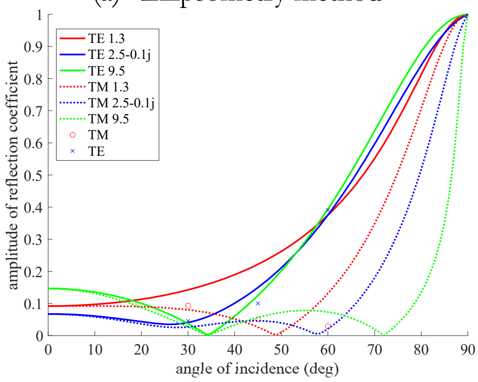
(Supported by the Ministry of Internal Affairs and Communications SCOPE 185103006)

Signals at high frequency bands, such as 5G, will suffer from a higher path loss. Hence, significant increase of base stations density, which is costly, is needed. In order to develop a cost-efficient wireless communication system, investigation of a radio propagation characteristic is necessary. Because permittivity has an important impact on a reflection and transmission in the radio propagation in this research, finding a convenient and accurate method for permittivity prediction becomes significant.

The goal of this research is to investigate the applicability of such methods. In this research, ellipsometry method and reflected power method were mainly considered to predict the measured permittivity of acrylic at 30-36 GHz frequency bands. In the experiment, amplitude of reflection coefficient with different permittivity values were compared. In Fig. 1a, some predicted results from ellipsometry method cannot fit well with the measurements, depicted by circle and cross markers for TM and TE waves, respectively. In contrast, results using reflected power method in Fig.1b was relatively more accurate since it had less discrepancy to the measurement.



(a) Ellipsometry method



(b) Reflected Power method

Fig. 1 Reflection coefficient amplitude

On the Modeling of Cylindrical Objects in the Radio Propagation Prediction

With the deployment of wireless communication services, the demand for the modeling of specific environment in the radio propagation prediction keeps increasing. Conventional propagation prediction tools, such as ray-tracing algorithms, may oversimply the complex architecture of the propagation channel which may lead to the accuracy of propagation prediction. This study focuses on the modeling of cylindrical objects such as utility poles, streetlamps traffic lights, pillars in the radio propagation prediction.

In research, the conventional raytracing simulator based on the geometrical optics (GO) approximation with a polygonal model is explained together with its inaccuracy. This study discusses the tradeoff between accuracy and complexity among several different simulation approaches in the radio propagation prediction. Then the accuracy of individual technique is evaluated by comparing with a theoretically accurate prediction approach of boundary element method (BEM). The complexity is discussed in terms of the implementation and data input compatibility with the conventional ray tracing approach.

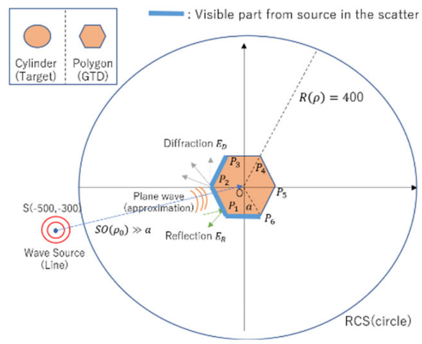


Fig.1 GO with a polygon model

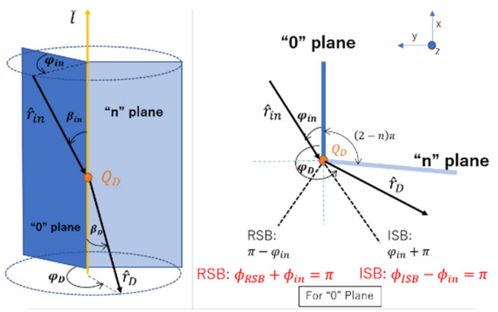


Fig.2 Canonical model of Scattering by GTD

Sakaguchi-Tran Laboratory

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.

Specially Appointed Assoc. Prof. Kazuki MARUTA

Specially Appointed Assoc. Prof. Kazuki MARUTA was born in 1984. He received the B.E., M.E., and Ph.D. degrees in engineering from Kyushu University, Japan in 2006, 2008 and 2016, respectively. From 2008 to 2017, he was with NTT Access Network Service Systems Laboratories and was engaged in the research and development of interference compensation techniques for future wireless communication systems. From 2017 to 2020, he was an Assistant Professor in the Graduate School of Engineering, Chiba University. He is currently a Specially Appointed Associate Professor in the Academy for Super Smart Society, Tokyo Institute of Technology. He is a member of the IEEE and the IEICE. He received the IEICE Young Researcher's Award in 2012, the IEICE Radio Communication Systems (RCS) Active Researcher Award in 2014, APMC2014 Prize, and the IEICE RCS Outstanding Researcher Award in 2018. He was a co-recipient of the IEICE Best Paper Award in 2018, SoftCOM2018 Best Paper Award and APCC2019 Best Paper Award.

Sakaguchi-Tran Laboratory

Cellular Networks by MmWave Massive Relay MIMO [15]

Introduction

With the advent of 5G (5th generation mobile communication system) and future communication technologies, autonomous driving technologies and IoT are expected to change the way we spend our lives (ex. entertainment, work, meetings). As a result of these changes, users will demand higher data rates for high-definition video viewing, work, and video meeting.

There are mainly two ways to achieve this. The first is the use of the broadband millimeter-wave band. The second is MIMO (Multiple-Input Multiple-Output) transmission. MIMO performs parallel transmission by putting different information on a multipath, a path with low correlation. In 5G, the introduction of millimeter waves has been decided, but there is a drawback that multipath cannot be obtained due to the propagation loss and straightness of millimeter waves.

Massive Analog Relay MIMO System

Millimeter-wave Massive Analog Relay MIMO can generate MIMO channel response artificially by using a large number of analog RSs. The system enabled MIMO transmission, which was difficult to achieve in millimeter-waves, and that the channel capacity was significantly improved. The analog RS node has two sides, a receiving side, and a transmitting side, in both of which the beamforming can be actively performed according to the location of the UE in real-time. we adopt the Amplify-and-Forward type to reduce the delay of data transmission that is one of the main requirements of 5G.

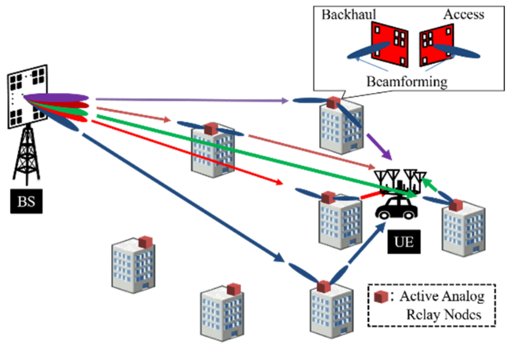


Fig. 1: Massive Relay MIMO System

Simulation Analysis

Fig. 2 shows a model of the Massive Analog Relay MIMO system applied to an urban area. The RS is placed on top of each building and the UE is moved among the buildings to calculate the channel capacity at 5m intervals. Fig. 3 shows the channel capacity. It compares the case without relay stations (w/o hop), single-hop, and multi-hop. Multi-hop allows the formation of many artificial propagation paths, which greatly improves the channel capacity. As a result, we can confirm that the channel capacity is greatly improved even in the non-line-of-sight environment. These results show the effectiveness of Massive Relay Analog MIMO.

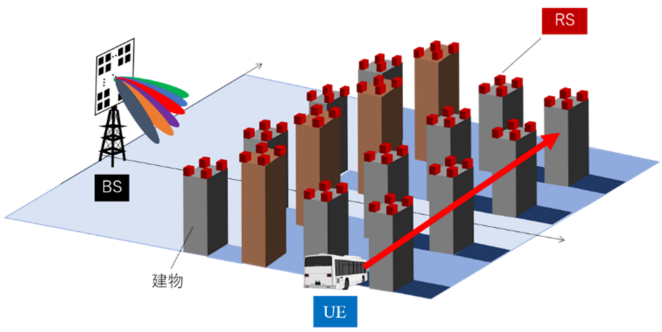


Fig. 2: Coverage characteristic

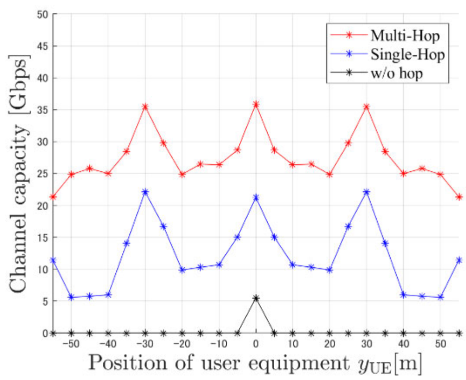


Fig. 3: Channel capacity

MmWave V2X Communications and Smart Mobility Testbed [3]

Background

Automated driving vehicles are expected to be the killer application of 5G and the solution to traffic problems. For example, today's traffic accidents are mainly caused by human failures, but automated driving vehicles are controlled by electronics instead of human, and thus are expected to effectively reduce traffic accidents. A great challenge is that automated driving vehicles must have full information of the environments without any blind spot, which often appears due to the limited LOS/FOV of onboard sensors and could result in false detections of on-road objects and lead to collision accidents. The cooperative perception is one of the most promising ways to address the challenge. Its key idea is to share the real-time sensor data among infrastructures and vehicles through wireless communications to eliminate the blind spots cooperatively.

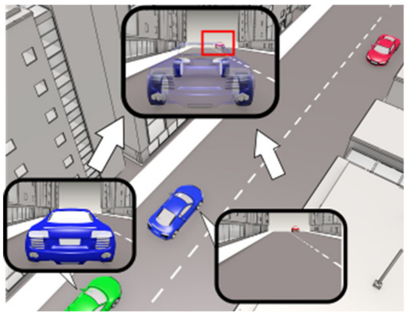


Fig. 1 Concept of cooperative perception

Smart Mobility Testbed

In 2020, Sakaguchi lab has initiated the construction of smart mobility testbed in Ookayama Campus. This activity is a step forward after conducting various V2X proofs-of-concept in last fascial year, which laid the groundwork for the practical utilization of mmWave in advanced V2X use cases specified by 3GPP and 5GAA. To increase the integrity and fidelity of smart mobility experiments, we have introduced COTS products, i.e. a refitted drive-by-wire electrical vehicle, installed necessary facilities (e.g. antennas) and set up software environments (Autoware) for connected automated driving. Figure 2 shows the established connected automated vehicle (CAV) platform. Although the vehicle relying on on-board sensors can already perform automated driving functions such as localization, object detection, and route planning, the involvement of V2X will further enhance its perception capability, thus significantly improving the driving safety and optimizing maneuver decisions.

Fig. 2 CAV platform

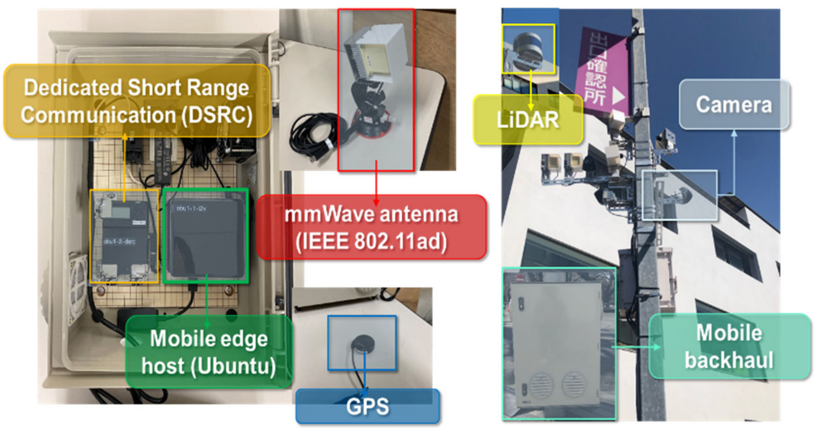


Fig. 3 Dedicated V2X infrastructures (OBU, RSU)

To increase the system reliability, we assembled dedicated V2X hardware. The deployed V2X infrastructures include on-board units (OBU) and road side units (RSU). Their compositions are shown as fig. 3. Comparing to other existing smart mobility testbeds, ours incorporates the most advanced V2X technology, i.e. mmWave V2X, and the platform will be further extended in the near future with standardized 5G system.

Sakaguchi-Tran Laboratory

Radio Resource Management (RRM) for mmWave V2V communications [6]

V2X communications has been identified as a critical technology to compensate for the restriction of sensors, break the line-of-sight constraint, acquire more data from surroundings (e.g., blind area information), and ultimately enhance the overall contextual awareness of connected vehicles. However, sharing sensor information on V2X communications like a precise three-dimensional map requires ultra-high data rate and ultra-low latency. Therefore, mmWave with ultra-wide continuous bandwidth has a potential to support ultra-high data rate.

There are lots of challenges in RRM for mmWave V2X communications such as interference control of V2V communications. To improve the reliability of V2V communications, allocating a single mmWave channel and applying a novel antenna configuration method called "ZigZag" for all V2V links as shown in Fig.1. This research improved spectrum utilization and ensured higher throughputs (over 1 Gbps) on V2V links in the dynamic vehicular environment with interference.

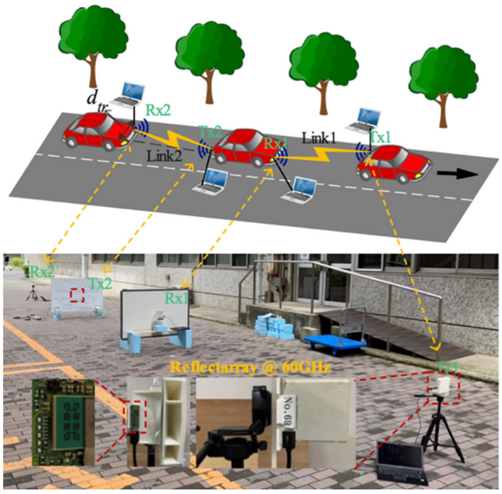


Fig. 2 ZigZag antenna configuration

Market Design of MEC 5G Ecosystem [4][18]

The emerging 5G networks will bring an unprecedented promotion in transmission data rates. However, the satisfaction of some service requirements is still in dilemma, especially the end-to-end (E2E) latency which varies in different applications. Multi-access edge computing (MEC), a promising technology in 5G cellular networks, can provide ultra-low E2E latency and reduce traffic load on mobile backhaul networks. The potential benefits of MEC for 5G and Beyond services have been explored by preliminary studies. What remains is the uncertainty of revenue from the investment of MEC which will shake operators' decisions about *whether* and *how* to deploy MEC in cellular networks. We designs a MEC-assisted 5G and beyond ecosystem inclusive of three players as shown in Fig.2 : private telecom operators, backhaul, and cloud service owners. We propose a revenue maximization model for private telecom operators and cloud service owners to minimize the cost from the end-user perspective while satisfying the latency requirement. The derived model indicates that two players' revenues can be maximized by optimizing MEC resources and backhaul capacity. The game-theoretic analyses also reveal the optimized hybrid strategy of MEC and cloud for efficient mobile traffic management as shown in Fig.3.

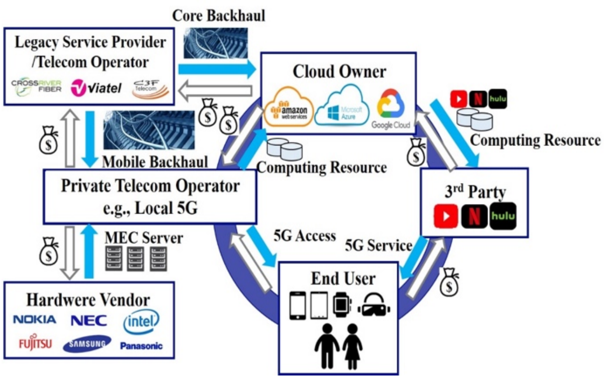


Fig.2 MEC Ecosystem

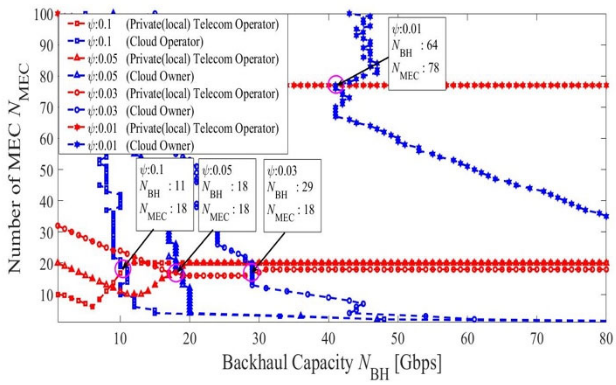


Fig.3 Optimized resources with latency requirements

Context-Based MEC Platform for Augmented-Reality Services in 5G Networks [16][17]

Augmented reality (AR) has drawn great attention in recent years. However, current AR devices have drawbacks, e.g., weak computation ability and large power consumption. To solve the problem, mobile edge computing (MEC) can be introduced as a key technology to offload data and computation from AR devices to MEC servers via 5G networks. To this end, a context-based MEC platform for AR services in 5G networks is proposed in this paper. On the platform, MEC is employed as a data processing center while AR devices are simplified as universal input/output devices, which overcomes their limitations and achieves better user experience.

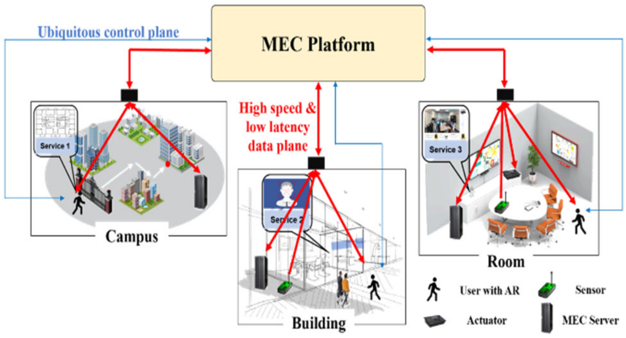


Fig.1 Application Scenarios of Platform

Moreover, the proof-of-concept (PoC) hardware prototype of the platform, and three typical use cases providing AR services of navigation and face recognition respectively are implemented to demonstrate the feasibility and effectiveness of the platform. Finally, the performance of the platform is also numerically evaluated, and the results validate the system design and agree well with expectations.

Some application using 5G and AR have been proposed. One of them is "Blind Spot Vision for Safe Driving Application". In this application, the blind spot information obtained by roadside unit is processed by the on-board units and then transmitted to the AR glass. By reducing the processing of the AR glass, it will be possible to support driving-related use cases where latency is an issue. In the future, more convenient services will be created by developing such services that take advantage of the characteristics of AR glass and the strengths of MEC.

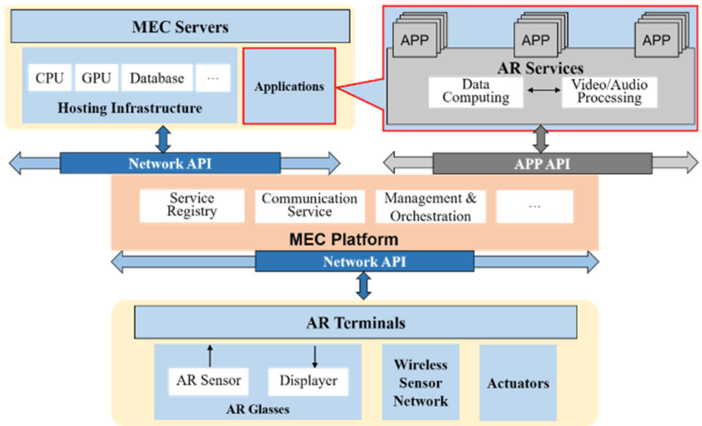


Fig.2 System Operation Mechanism with MEC Platform

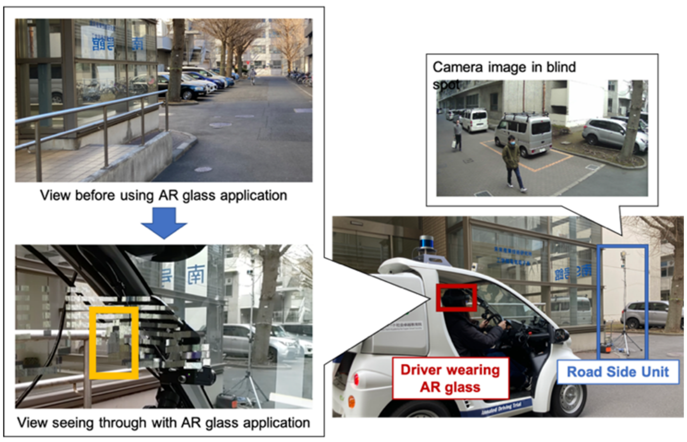


Fig.3 Example of AR application "Blind Spot Vision for Safe Driving" Application

Sakaguchi-Tran Laboratory

Multi-UAV Full-duplex Communication System [8][10][20][21]

System Architecture

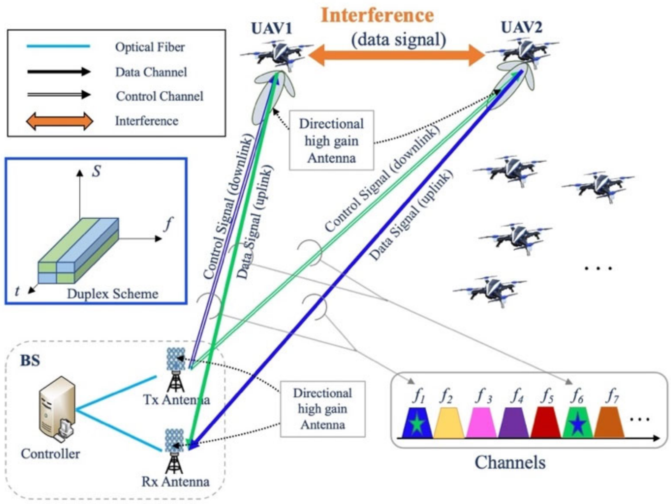


Fig. 1. Architecture of the Multi-UAV Full-duplex Communication System

The wireless transmission of ultra-high-resolution sensing data such as video from UAVs has attracted great attention. To further improve the system efficiency, it is expected to introduce multiple UAVs to provide more sensing information. However, when the multiple UAVs are simultaneously transmitting, the conventional multiplexing communication system for UAVs suffers the large co-channel interference and the consequent limited coverage, which severely decrease the throughput and destabilizes the remote control of UAVs. To address the problems, we propose a new design of a multi-UAV full-duplex system for joint high-specification video transmission and stable flight control, as shown in Fig. 1. In the system, high gain directional antennas are employed in both of the UAVs and BS, and each channel is reused by the uplink and downlink of a pair of UAVs. Moreover, to mitigate the co-channel interference among UAVs, the channel allocation is equated to a UAV trajectory planning problem. In the proposed system, the high spectrum efficiency and low UAV hardware complexity are achieved, and the co-channel interference is also significantly mitigated. The simulations are also conducted to validate the system, and the results confirm the design.

Inter-System Interference Avoidance

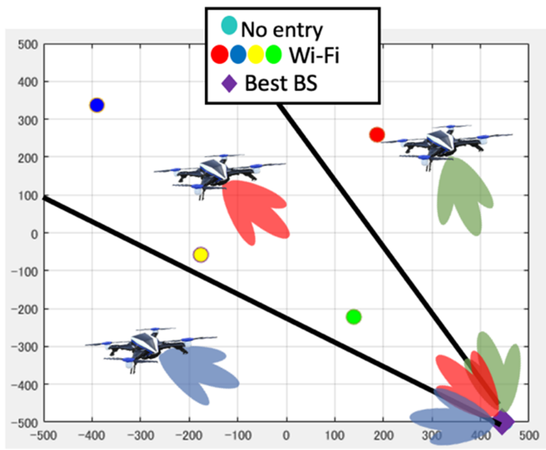
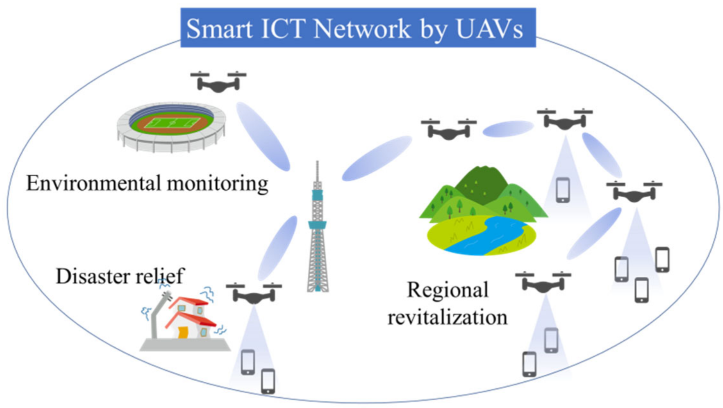


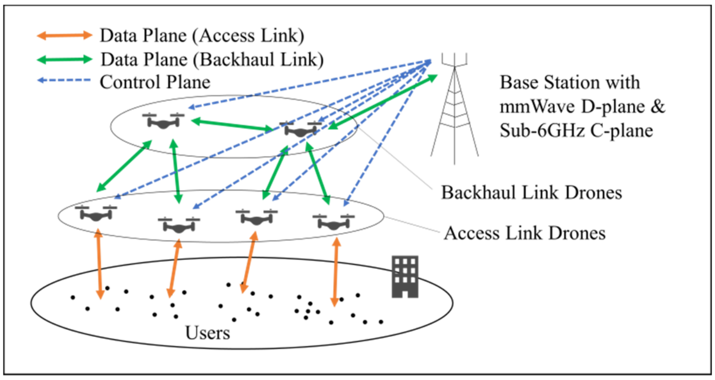
Fig. 2. Multiple drones can be used to fly over the entire area.

The spectrum sharing conditions between the proposed multi-UAV communication system and the existing wireless LAN systems on the ground using the same frequency band are analyzed and established. To avoid the inter-system interference, the flyable area of each UAV, in which the spectrum sharing conditions are satisfied, is derived. The optimal BS location is also selected to maximum the flyable area of UAVs. The validation simulation is conducted, in which four Wi-Fi devices are setup within 1 km^2 area, and the UAVs' flyable areas of proposed system and the conventional systems, which use the omni-directional antennas and high transmission power, are compared. The simulation results confirm that in the proposed system, by predefining the flyable area of each UAV, the UAVs can cover the entire target area and coexist with wireless LAN systems, while the conventional systems result in 0% of the flyable area ratio at an altitude of 30m. The spectrum sharing scheme with other wireless systems was illustrated in Fig.2.

Optimal Network Management for UAVs [5][9][12][14]



Due to the increase in the number of users and the development of information technology, the speed, capacity and coverage required for communication are increasing. For this reason, the use of airborne base stations with UAVs has been proposed. Airborne base stations can be placed freely without being affected by the ground environment and can be operated flexibly in both space and time. In addition, there are fewer obstacles in the sky, and the coverage increases due to less attenuation. In this study, we used millimeter-wave and divided UAVs into two types: access-link drones that communicate directly with users and backhaul drones that relay between them and a base station on the ground and considered the placement problem for each.



As the setting of this study, the frequency used for communication is divided into data plane and control plane. In the data plane, millimeter wave is used to realize high-speed and large-capacity communication. In the control plane, each UAV communicates directly with the base station, so a lower frequency band is used. The first step is to determine the location of the access link drone.

The placement of the access link drones was determined by incorporating the smallest-circle problem of the geometry problem in addition to the previous method using the K-means method. By incorporating the smallest-circle problem, the offered data rate was improved as it reduces interference and utilizes power more efficiently than the previous method. In addition, we were able to raise the outage of the offered data rate without decreasing the average offered data rate for the most part by introducing fractional frequency reuse to increase the frequency utilization efficiency.

For the backhaul drones, we assume that the location of the access link drones is fixed. The base station is divided into sectors where backhaul drones are allocated properly to eliminate the bias of drones accommodated in each sector. Using a genetic algorithm, we set the objective function to maximize the overall capacity. The drones are allowed to change the orientations of their antennas freely, and these of the base station are assumed to be fixed. The overall capacity is improved when comparing the case of access link drone only and the case after optimization.

Hirokawa Laboratory

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

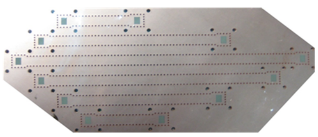
received the B.S., M.S. and D.E. degrees in electrical and electronic engineering from the Tokyo Institute of Technology, Tokyo, Japan, in 2008, 2011 and 2014, respectively. He was a Research Fellow of the Japan Society for the Promotion of Science (JSPS) in 2013. From 2014 to 2017, he worked at Mitsubishi 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.

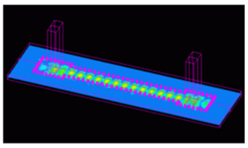
Dr. Tomura received the Best Student Award from Ericsson Japan in 2012 and the IEEE AP-S Tokyo Chapter Young Engineer Award in 2015 and Young Researcher Award from IEICE technical committee on antennas and propagation in 2018. He is a member of IEEE and IEICE.

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.

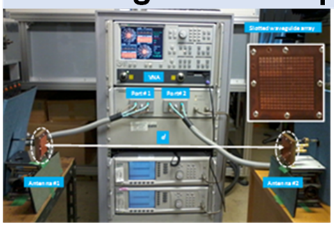
Post-wall waveguide

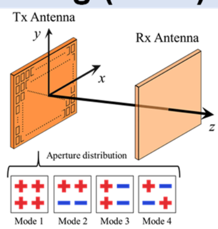




- Known as Substrate Integrated Waveguide (SIW)
- Published in the IEEE transaction in 1998 (Total citation: 308, Web of Science, 2017/6)
- Used as microwave and millimeter-wave band low-loss waveguide

Rectangular coordinate orthogonal multiplexing (ROM)

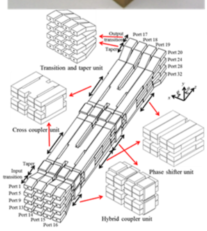




- Published in the IEEE transaction in 2017
- Equivalent to OAM transmission in the optical communication system, and apply to microwave and millimeter-wave applications

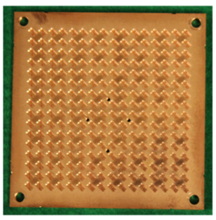
2-D beam-switching one-body Butler matrix

- 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)

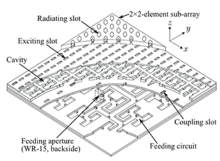


- $4^2 \times 4^2$-way one-body 2-D beam-switching waveguide Butler matrix
- Reduced its length and conduction losses by half.
- Reduced the number of components and volume.

Corporate-feed Slot Array Antenna with Plate-laminated Waveguide

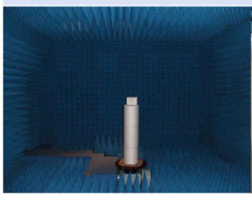


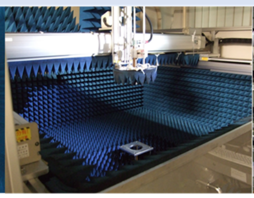
- Published in the IEEE transaction in 2011.
- After that, research is also started in Sweden, Singapore, China, etc.
- Designed in various frequency bands like 38-GHz band, 60-GHz band, and 120-GHz band, etc.



✓ 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

Transmission Enhancement in Rectangular-Coordinate Orthogonal Multiplexing by Excitation Optimization of Slot Arrays Based on the Scattering Parameters

In the ROM (rectangular-coordinate orthogonal multiplexing) transmission antenna system, the transmission between the Tx and Rx antennas attenuates as the propagation distance increases due to the split beam divergence. Excitation optimization is a good way to enhance the channel capacity at a given distance. It enables both larger capacity and longer communication distance simultaneously in the multiplexing transmission system. In [2], the system was analyzed by replacing the array elements with infinitesimal small dipoles, and the effect of the mutual couplings among these dipoles as well as multiple reflections between the Tx and Rx antennas were not considered. We presents a new method to get the best excitation distribution using the scattering parameters, including mutual couplings.

A new model is introduced by considering the actual antenna structure of monopulse corporate-feed waveguide slot array antenna. We can obtain an enhanced transmission performance by optimizing the amplitude and phase distribution based on the scattering parameters. A new design model is introduced to get the scattering parameters of the actual ROM antenna system. Figure 1 shows the proposed simulation model. The full-size model contains two identical arrays of antennas placed face to face with a 400mm distance. Considering the actual antenna structure, each array possesses 8×8 input ports and 16×16 radiating elements. That means the minimum radiation unit is a 2×2-element subarray. To reduce the calculation, the full-size model can be simplified to the quarter size model based on symmetry. PEC or PMC boundary is introduced at the *xoz* and *yoz* planes according to the operating mode. Other surfaces are set to radiation boundary conditions in the HFSS simulation. By using this simulation model, we can get the desired scattering parameters between the Tx and Rx antennas.

Detail of your research such as explanation of antenna structure and results.

Base on the new design method and model. The transmission of four modes get improved by 1dB and the capacity is increased by 7%, which is equivalent to a 7%-ratio increase in bandwidth.

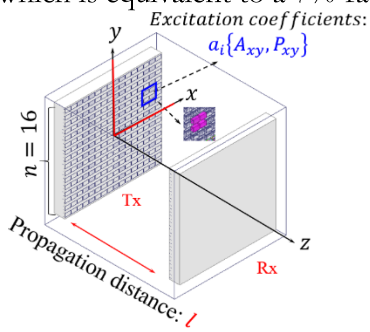


Fig. 1 Antenna structure

Referrence

[1] K. Tekkouk, J. Hirokawa and M. Ando, "Multiplexing Antenna System in the Non-Far Region Exploiting Two-dimensional Beam Mode Orthogonality in the Rectangular Coordinate System," IEEE Trans. Antennas Propag., vol. 66, no. 3, pp. 1507-1515, March 2018,

[2] R. Ohashi, T. Tomura, and J. Hirokawa, "Transmission Enhancement in Rectangular-coordinate Orthogonal Multiplexing by Excitation Optimization of Slot Arrays for a Given Distance in the Non-far Region Communication," IEICE Trans. Commun., vol. E103-B, no. 2, pp. 130-138, Feb. 2020.

[3] X. Xu, J. Hirokawa, and M. Ando, "Plate-laminated waveguide monopulse slot array antenna with full-corporate-feed in the E-band" IEICE Trans. Commun., vol. 100, no. 4, pp. 575-585, Apr. 2017.

Rectangular-coordinate Orthogonal Multiplexing including Modulation

Rectangular-coordinate orthogonal multiplexing (ROM) is proposed as an equivalent scheme to orbital angular momentum (OAM) multiplexing, which is a spatial division multiplexing technology in the millimeter-wave band. The multiplexing utilizing the orthogonality of the field polarity distribution is carried out between the Tx (transmitting) and Rx (receiving) antennas facing each other in the non-far region as shown in Fig. 1.

The antenna for ROM consists of the corporate-feed waveguide slot array antenna for the 60GHz band and a beam switching circuit. The aperture of the 16x16-element corporate-feed waveguide slot array antenna is divided into four 8x8-element subarrays, and each of them is excited by a beam switching circuit. The antenna has four ports, and four orthogonal modes corresponding to each input port are generated in the Tx side, and they are separated without signal processing in the Rx side due to the beam switching circuit.

The simulation considering modulation is conducted by using Simulink in MATLAB. The results show that if the crosstalk in multiplexing is sufficiently suppressed, it is possible to obtain BER comparable to those of the single-mode case.

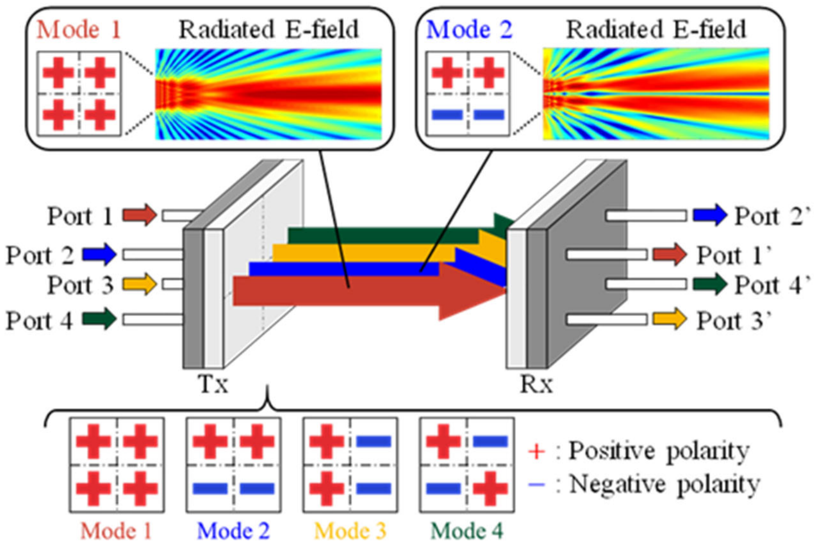


Fig. 1 4-mode ROM system

Referrence

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[3] R. Ohashi, T. Tomura, and J. Hirokawa, "Transmission enhancement in rectangular-coordinate orthogonal multiplexing by excitation optimization of slot arrays for a given distance in the non-far region communication," IEICE Trans. Commun., vol. E103-B, no. 2, pp. 130- 138, Feb. 2020.

Hirokawa Laboratory

Efficient Optimization of Bandwidth of the Element in a Multilayer Parallel-plate Slot Array

A wideband multilayer parallel plate slot array is proposed. To conduct the electromagnetic analysis efficiently, a method of moments (MoM) based on eigenmode expansion is performed on the element. Compared to the conventional method relying on simulation by HFSS, the analysis by the MoM maintains excellent accuracy whereas more time-efficient. A genetic algorithm is then invoked in the analysis to optimize all variable parameters with an aim for wide fractional bandwidth.

The element mainly comprises three layers, as displayed from an exploded view in Fig. 1. The bottom layer #1 consists of a short-end rectangular hollow waveguide and a coupling slot on the broad wall for feeding. The layer #2 ranges from the coupling slot plate to the radiating slot plate, where 2×2 wide rectangular slots are arrayed . Under the slots, there is a substrate plate made of PTFE and an air layer. The top layer #3 is constituted by an air layer and a metal plate with 2×2 parasitic slots. The introduction of the layer #3 will contribute to the enhancement of the bandwidth of the element.

All variable parameters in the model are optimized simultaneously and the ultimate optimized fractional bandwidth with reflection less than -14 dB is 16.0% (55.5 GHz – 65.1 GHz). Excellent agreement with the HFSS simulation is obtained, verifying the validness and accuracy of the proposed method. The bandwidth is not only much enhanced from the 7.7% of the similar three-layer structure acquired by the conventional HFSS simulation, but also better than the optimum 13.0% of the two-layer structure (without layer #3) designed in the same method [1], [2]. Another advantage of the proposed method is the much reduced analysis time. Calculating the reflections on 29 frequency points for one set of parameters takes less than 20 seconds, which is around 1/10 of that by the HFSS.

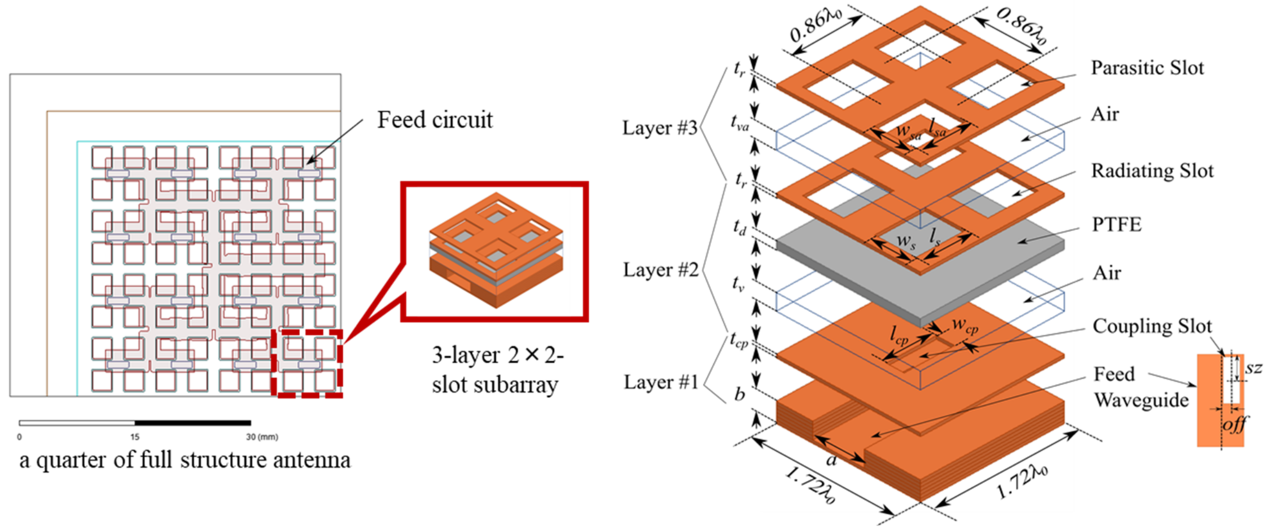

Fig. 1 Antenna structure

Referrence

[4] H. Irie and J. Hirokawa, "Perpendicular-corporate feed in three-layered parallel-plate radiating-slot array," IEEE Trans. Antennas Propag., vol. 65, no. 11, pp. 5829-5836, Nov. 2017.

[5] S. Ji, T. Tomura, and J. Hirokawa, "Wideband Design of a Two-Layer Parallel-Plate Slot Array Antenna with Hollow Waveguide Corporate Feeding Network," IEEE AP-S URSI Intl. Symp., TH-UB.1A, July 2020.

Wideband Design of a H-plane T-junction by Shape Optimization for a Corporate-feed Circuit of a Waveguide Slot Array in the 60GHz-band

Corporate-feed waveguide slot array antenna is a planer antenna consisting of the radiating part and the feeding part. Corporate feeding provides a wideband characteristics and waveguide feeding provides high efficiency. Since it is easy to fabricate by diffusion bonding laminated plates, it has been used for millimeter-wave fixed wireless communications.

When designing this antenna, we need to design the 2x2-slot element which is the radiating unit and the feeding circuit separately. We can optimize the parameters of the 2x2-slot element by combining a fast numerical analysis method using the Method of Moments with the Genetic Algorithm (GA) and thus achieve the maximum bandwidth. On the other hand, the feeding circuit consists of the H-plane T-junctions and the H-plane H-junction which include inductive walls and irises. Even with this structure, broadband characteristics are achieved, but we aim to optimize the shape of the H-plane T-junction to maximize the bandwidth as in the 2x2-slot element.

We analyze the half model of the H-plane T-junction with PMC shown as Fig. 1 to reduce the model to halve its original size and to reduce the analysis time, Since the electric field becomes zero at the center of the broadwall of the waveguide. Using this model, we derive the reflection from the two-dimensional Finite Element Method. The colored arrows in Fig. 1 show the shape change region and the length is 0.9λ. We introduced the nodes in the shape change region and optimized them by GA without affecting the neighboring elements. The reflection bandwidth lower than -28.9 dB of the optimized H-plane T-junction is 23.9%. Compared with the conventional model, the bandwidth is improved by 6.2%.

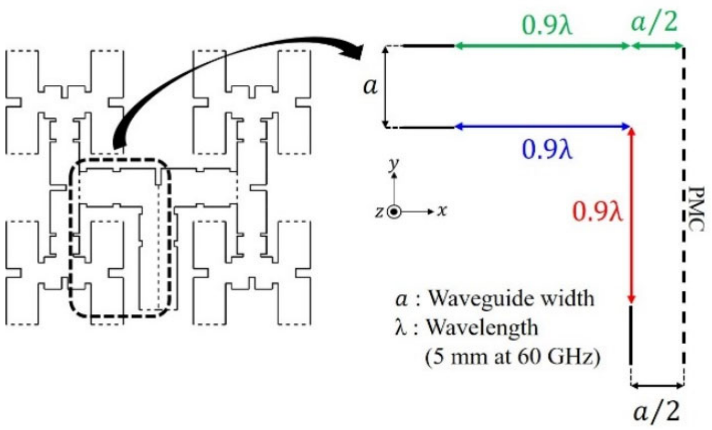

Fig. 1 Analysis model of the H-plane T-junction

Referrence

[6] W. Kuramoto, T. Tomura and J. Hirokawa, "Wideband Design of a H-plane T-junction by Shape Optimization for a Corporate-feed Circuit of a Waveguide Slot Array in the 60GHz-band", International Symposium on Antennas and Propagation (ISAP), Jan. 2021.

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Hirokawa Laboratory

Design of Longitudinal Coupling Slots with Matching Walls for a Rectangular Parallel Plate Slot Array Antenna

A rectangular parallel plate slot array antenna with a traveling-wave feeder beneath was proposed. The structure is attractive for millimeter-wave applications due to its lightweight and high efficiency. In [1], a waveguide feeder with center-inclined coupling slots and reflection-canceling walls was designed by the method of moments (MoM) with fast speed. However, it would cause a large vibration of both phase and amplitude field distributions in the parallel plates by using tilted slots. This is undesired because a uniform field distribution is needed for achieving high antenna efficiency. A novel feeder with longitudinal coupling slots is proposed and designed by HFSS.

Fig.1 shows the antenna structure with the new feeder network. The antenna aims to operate in 9.50GHz-9.80GHz. The antenna panel is truncated by hard walls at the edges for achieving TEM wave propagation. The waveguide feeder with coupling slots is installed underneath the parallel plates. A TE_{10} mode traveling wave from the antenna input couples with the parallel plates through the coupling slots. Longitudinal coupling slots cut along the center of the waveguide broad wall are employed for reducing vibration of field distribution in the parallel plates. A coupling wall for achieving the desired coupling amount and an inductive wall for reflection-canceling are introduced corresponding to each slot, which are together termed as matching walls. The coupled waves then propagate in both $+y$ and $-y$ directions in the parallel plates and radiate through horizontal radiating slot pairs.

The design aims to suppress reflection in the waveguide and achieve uniform field distribution in the parallel plate region. A design procedure of the feeder network is given as follows. (1) Design the individual slot by the element model. External mutual coupling effect among the coupling slots are included by introducing periodic boundary conditions (PBC) in the side walls in the parallel plates. The required coupling factor for each slot is $1/n$ to ensure a uniform excitation of the parallel plates. (2) Design the slot array. The distance d_k between the centers of the adjacent slots is optimized to guarantee in-phase excitation through all the slots. (3) Design the τ-junction with two center slots. The full structure consisting of the designed waveguide feeder with antenna panel is simulated in HFSS. A peak directivity of 37.0dBi and 86% aperture efficiency is achieved. Reflection below -19 dB is achieved throughout the target bandwidth. Compared to the results in [1], the novel feeder obtains 1.0dBi directivity and 18% aperture efficiency enhancement. The peak directivity is at the center frequency and the reduction within 300MHz bandwidth is -2.3dB.

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] T. Wang, T. Tomura, and J. Hirokawa, "Design of Longitudinal Coupling Slots with Matching Walls for a Rectangular Parallel Plate Slot Array Antenna," Intl. Symp. Antennas Propag., Jan. 2021.

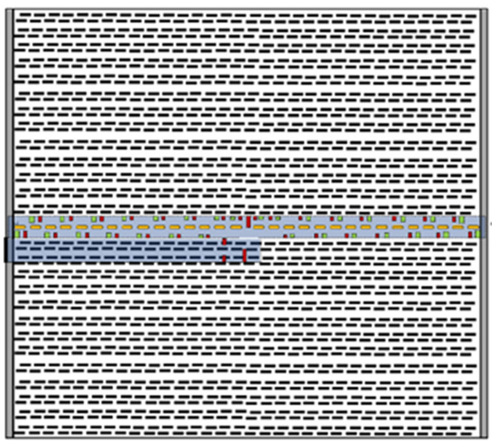

Fig. 1. Antenna Structure

Transmission Enhancement for Radial Line Slot Antennas in Non-Far Region Using a Feeding Slot with Better Rotating Mode

Brief Introduction

Near-field communication using a radial line slot array (RLSA) antenna was presented in [1]. The antennas suffered from a reduction in transmission due to multiple reflections in the non-far region [2]. The finding in [3] indicates that the transmission between the Tx and Rx antennas is significantly related to the aperture field distribution of the antennas. To improve the uniformity of the aperture field distribution, designs of new feeding slots are investigated.

Antenna Structure & Results.

Fig. 1 shows the structure of a 4-turn RLSA. It is divided mainly into two parts: 1) the feeding part has a rectangular feeding waveguide with a coupling slot 2) The radiating part is composed of a poly tetra fluoro ethylene (PTFE)-filled radial waveguide and an array of radiating slots etched on a copper plate with bulk conductivity of 5.8×10^{7} S/m. The feeding waveguide, cross slot, and radial waveguide are of aluminum with bulk conductivity of 3.8×10^{7} S/m. The operational frequency of the RLSA is 5.8 GHz. The antenna supports circular polarization. The identical RLSAs are used for the Tx and Rx antennas and the transmission distance is in the non-far region.

To reduce the amplitude ripple in the phi-direction inside the radial waveguide, two types of feeding slots, straight and dog-bone cross-slots, are investigated. Both are designed to excite the uniform amplitude and rotating phase field in the phi-direction in the radial waveguide. The dog-bone cross-slot gives the lowest amplitude ripples of 1.85 dB. The new cross-slot has slightly higher amplitude ripples of 2.54 dB, while the old cross-slot has the highest amplitude ripples of 4.70 dB among the three feeding slots. By adopting the new slot designs, the transmission level of the RLSAs using the new cross-slot and the dog-bone one increases by approximately 2 dB from that using the old cross-slot ([1], [2], and [3]). Moreover, the transmission ripples for the RLSAs using the new cross-slot and the dog-bone one reduce by 2.15 dB and 2.25 dB respectively. The results point out that the lower the amplitude ripples of E-field in the phi-direction in the radial waveguide, the lower the transmission ripples.

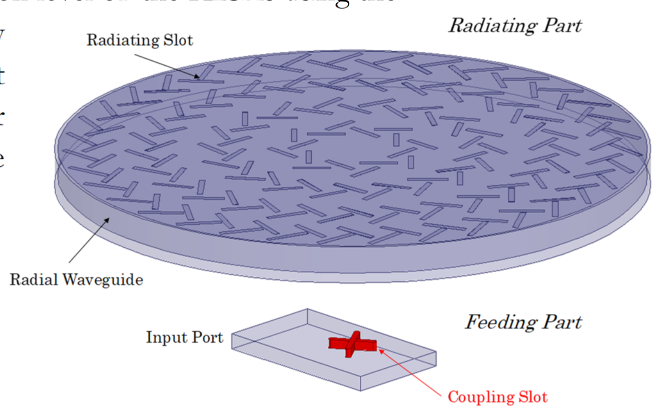

Fig. 1 Antenna structure

Reference

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Okada Laboratory

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

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From 2000 to 2003, he was a Research Fellow of the Japan Society for the Promotion of Science in Kyoto University. In 2003, he joined Tokyo Institute of Technology as an Assistant Professor. He is now a Professor of Electrical and Electronic Engineering at Tokyo Institute of Technology, Tokyo, Japan. He has authored or co-authored more than 400 journal and conference papers. His current research interests include millimeter-wave CMOS wireless transceivers for 20/28/39/60/77/79/100/300GHz for 5G, WiGig, satellite and future wireless system, digital PLL, synthesizable PLL, atomic clock, and ultra-low-power wireless transceivers for Bluetooth Low-Energy, and Sub-GHz applications.
Prof. Okada 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 IEICE Achievement Award in 2019, the DOCOMO Mobile Science Award in 2019, the KDDI Foundation Award in 2020, the IEEE CICC, Best Paper Award in 2020, and more than 40 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, European Solid-State Circuits Conference, Radio Frequency Integrated Circuits Symposium, 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, a Distinguished Lecturer of the IEEE Solid-State Circuits Society.

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Assistant Professor Jian Pang

Special-Appointed Assistant Professor Jian Pang received the Bachelor and Master degrees from Southeast University, Nanjing, China, in 2012 and 2014, respectively, and the Ph.D. degree from the Department of Physical Electronics, Tokyo Institute of Technology, Tokyo, Japan, in 2019. From 2019 to 2020, he was a Post-Doctoral Researcher with Tokyo Institute of Technology.

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Dr. Pang was a recipient of the IEEE SSCS Student Travel Grant Award in 2016, the IEEE SSCS Predoctoral Achievement Award for 2018-2019, and the Seiichi Tejima Oversea Student Research Award in 2020. He serves as a reviewer of IEEE Journal of Solid-State Circuits, IEEE Transactions on Microwave Theory and Techniques, IEEE Transactions on Circuits and Systems I & II, and IEEE Microwave and Wireless Components Letters.

Our Research Interests

At Okada laboratory, we have been researching RF, analog and digital mixed signal integrated circuit design. Currently, we focus on the following research topics. In this report, we introduce the research highlight of this year about 1) 5G Transceiver, 2) 300GHz Transceiver, 3) SATCOM Transceiver

- 5G Phased-array Transceiver
- 100GHz/300GHz Transceiver
- Satellite Communication Transceiver
- Ultra-Low Power Bluetooth Low Energy Transceiver
- Ultra-Low Power All-Digital-PLL
- Synthesizable PLL
- Atomic Clock for Satellite Communication
- Wireless Power Transfer
- RF fingerprints

Okada Laboratory

A 28-GHz CMOS Phased-Array Beamformer Supporting Dual-Polarized MIMO with Cross-Polarization Leakage Cancellation

DP-MIMO improves the data rate and spectrum efficiency in 5G NR. A dual-polarized phased-array transceiver can transmit two independent data streams simultaneously through the H- and V-polarized waves. However, the imperfection of antenna and the polarization rotation will cause cross-pol. leakage during the receiving, which degrades the channel capacity. Even with the MIMO processing, higher TX-to-RX SNR is required to maintain the same channel capacity. In this situation, the TX output power and efficiency will be significantly degraded due to the larger power back-off. Since a further improvement of cross-pol. isolation at the antenna side is not feasible, an active cancellation technique is demanded in 5G DP-MIMO systems.

Fig. 1 shows the block diagram of the beamformer chip. Area-efficient neutralized bi-directional architecture is employed to share the same signal chain between the TX and RX. Totally 8 beamformer elements (4H+4V) are integrated to support DP-MIMO. Each of the beamformer elements consists of a PA-LNA, a phase shifter and an isolation buffer. Detection circuits are also included for detecting the magnitude and phase mismatches between elements.

To improve the cross-pol. isolation, a cross-pol. leakage canceller is implemented along with the chip. Fig. 1 also shows the proposed H/V canceller. The H/V canceller in this work includes the H/V bi-directional VGAs and the H/V cancellation paths. The H/V bi-directional VGAs combine two VGA chains with reversed directions for supporting the bi-directional operation. For each cancellation path, two VGAs and a reflection-type phase shifter are utilized. The cancellation signals are generated for H-pol. and V-pol. at the TX side so that it can cancel the cross-pol. leakage caused by all through the TX/RX chip, package, PCB and antenna. The cancellation path covers a gain range of 38dB with less than 4° phase variation and a phase range of 360°. The consumed power for the cancellation path is 19mW.

Fig. 2 presents the asymmetric neutralized bi-directional PA-LNA. The mode selection is realized by switching the tail transistors. To maintain the cross-coupling capacitor neutralization in both operation modes, extra capacitors are added to the LNA transistors for compensating the size mismatch with the PA transistors. Regarding the antenna sharing, a switchable LC resonant network is utilized to maintain the required matching conditions for both PA and LNA modes. The measured PA-mode peak PAE is 33.1% at 28GHz, and the LNA-mode NF is 5.4dB.

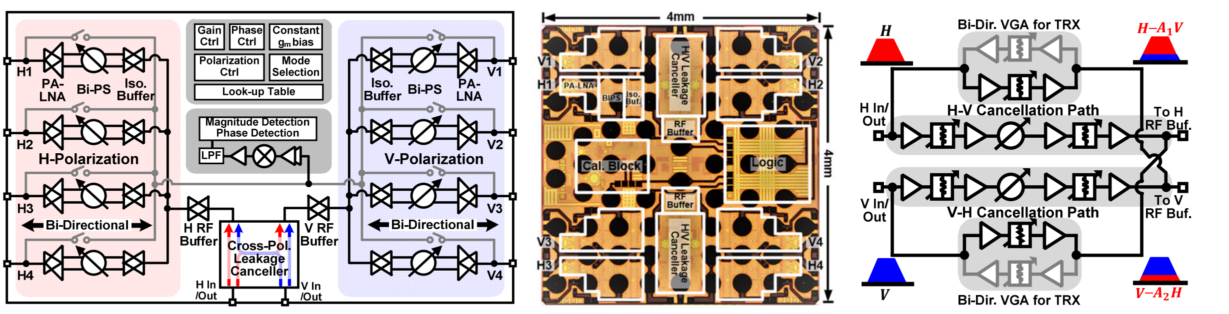


Fig. 1. Proposed 28GHz phased-array transceiver chip and proposed x-pol. leakage canceller.

The proposed chip is fabricated in a 65-nm CMOS process with WLCSP. The beamformer element in this work occupies only 0.48mm^2 with the help of the neutralized bi-directional architecture. To evaluate the over-the-air (OTA) performance, 16 of the packaged chips are implemented into the 64H+64V (16×4) beamformer modules. The H and V ports of each chip are connected to a 4×4 dual-polarized antenna array on the PCB. A saturated EIRP of 52.2dBm is realized by totally 64 elements.

Fig. 3 shows the TX-to-RX spectra before and after the cross -pol. leakage cancellation in the OTA measurement. Both TX and RX utilize a 2×2 dual-polarized array implemented with the proposed 4H+4V chip. Single-tone signals at 26.9GHz and 27GHz are sent to the H- and V-pols. of the TX array and received by the H- and V-pols. of the RX array. After the cancellation, the cross-pol. isolations are improved from 15dB to more than 41dB. 2×2 DP-MIMO measurements with two 400-MHz 5G NR signals is also conducted with and without the proposed cancellation. As also shown in Fig. 3, the TX-to-RX EVMs are improved to -30.0dB in 64QAM, and -29.7dB in 256QAM with the cancellation.

Finally, Fig. 4 shows the comparison between this work and the state-of-the-art dual-polarized 28GHz phased-array transceivers. The compact bi-directional beamformer element consumes minimized area. Thanks to the proposed cross-pol. leakage cancellation, the measured 2×2 DP-MIMO EVM in 256QAM is significantly improved to 3.3%.

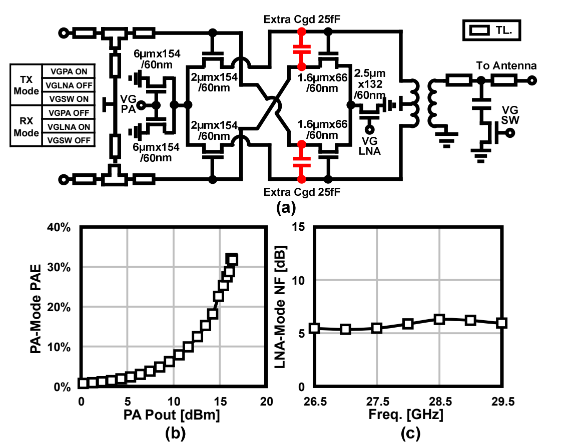


Fig. 2. Proposed cross-pol. leakage canceller.

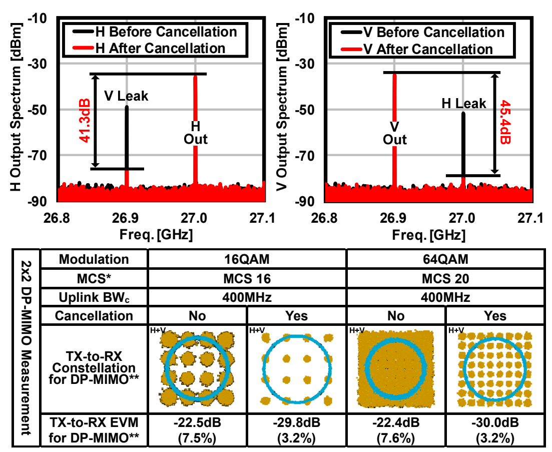


Fig. 3. Phase and gain calibration mechanism.

	This work		[1] IBM JSSC2017	[2] Qualcomm ISSCC2018	[3] UCSD RFIC 2018	[4] Tokyo Tech ISSCC2019
Process	65nm CMOS		0.13µm SiGe	28nm CMOS	0.18µm SiGe	65nm CMOS
Carrier Freq.	28GHz (n257)		28GHz	28GHz (n257)	29GHz	28GHz (n257)
TX P_{sat}/path	16.1dBm		16.4dBm	14.0dBm	N/A	15.1dBm
Integration/chip	8xBeamformer, Mag&Phase Cal., Cross-Pol. Leak Cancel		16xH-TRX, 16xV-TRX, IF, LO (w/o PLL)	24xTRX, IF, LO	8xBeamformer	8xBeamformer
X-pol. Leak Cancellation	Yes		No	No	No	No
Rotation btw. TX & RX	Yes		No	No	No	No
X-pol. Isolation for DP-MIMO	41.3dB for V pol. 45.4dB for H pol.		N/A	N/A	36dB for V pol. 27dB for H pol.	20.2dB
5G NR 2x2 DP-MIMO	64QAM	256QAM	N/A	N/A	N/A	64QAM
	EVM=3.2%	EVM=3.3%				EVM=4.9%
P_{DC}/path	TX:181mW RX:88mW		TX:319mW RX:206mW	TX:119mW (P_{1dB}) RX:42mW	TX:220mW RX:150mW	TX:232mW RX:112mW
Area/path	0.48mm^2		2.55mm^2	0.68mm^2	1.62mm^2	0.59mm^2

Fig. 4. Comparison Table.

A 300GHz-Band Phased-Array Transceiver Using Bi-Directional Outphasing and Hartley Architecture in 65nm CMOS

A CMOS bi-directional phased-array transceiver that covers the frequency range of 242-280GHz is implemented. The array consists of 4 elements with beamforming ability in the H-plane of the on-PCB Vivaldi antennas. The LO phase generation scheme enables two different architectures for TX and RX modes. The TX mode utilizes an outphasing architecture while the Hartley architecture is adopted in the RX mode. The maximum achieved baud rates in the TX mode and the RX mode are 26Gbaud and 18Gbaud, respectively.

Achieving wireless communication using CMOS at frequencies around 250GHz and above is challenging, considering the limited f_{max} of the CMOS transistors. So, a mixer-last TX / mixer-first RX architecture is usually used. In this work, outphasing is applied to increase the TX output power by operating the mixers at their saturated output power. The average output power of the TX is comparable to that of the power combining TXs as the back-off is not needed anymore. Fig. 5 shows the phased-array system architecture. Four elements with wideband Vivaldi antennas are stacked vertically, considering the short wavelength of the target frequency band. The circuit consists of two subharmonic passive mixers and two bi-directional IF distributed amplifiers in the signal path. The LO chain consists

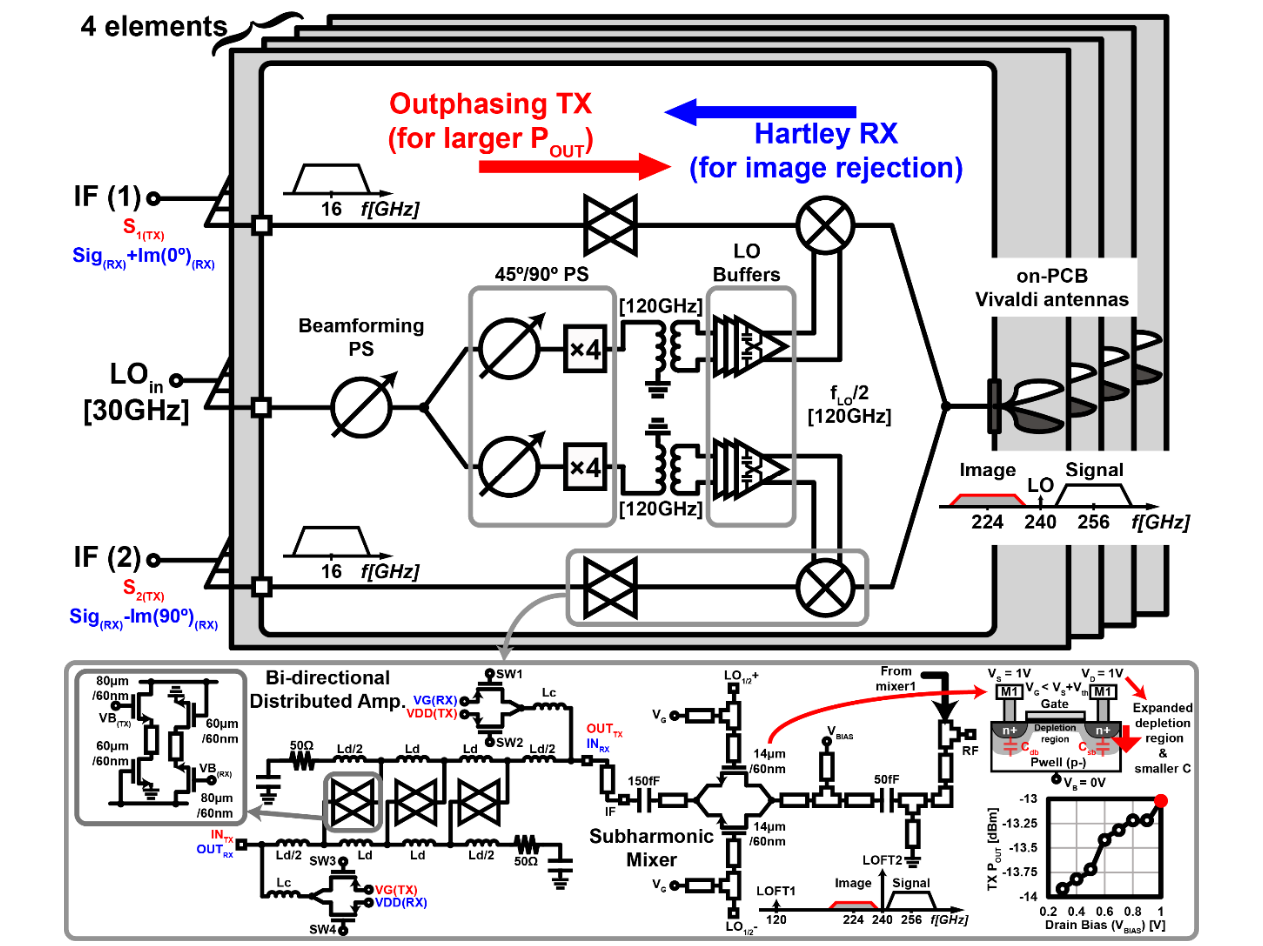


Fig. 5. Proposed CMOS 300GHz bi-directional phased-array transceiver architecture.

of three phase shifters, two frequency quadruplers, and LO buffers. Due to the subharmonic operation of the mixer, the IF signal is up- or down-converted by 240GHz. The mixer is based on the push-push doubler circuit. The 1V bias at the output of the mixer improves the output power as the parasitic capacitance between the source/drain and the bulk drops due to the high reverse bias.

The phased-array was implemented by stacking 4 PCBs with Liquid Crystal Polymer (LCP, ε_r=3) flexible substrate. The spacing between every two elements is around 0.7mm (close to $\lambda/2$ at f_{center}). A part of the PCB is left flexible to fit the connectors. The flip-chip process is used to connect the CMOS die to the PCB. IF and LO signals are amplified and split externally. The H-plane radiation patterns of the array are shown in Fig. 6.

Fig. 7 shows the micrograph of the TRX, which was fabricated in 65nm CMOS process. The total chip area is 4.17mm^2. Fig. 8 shows a comparison between this work and the other state-of-the-art CMOS 200~300GHz transceivers.

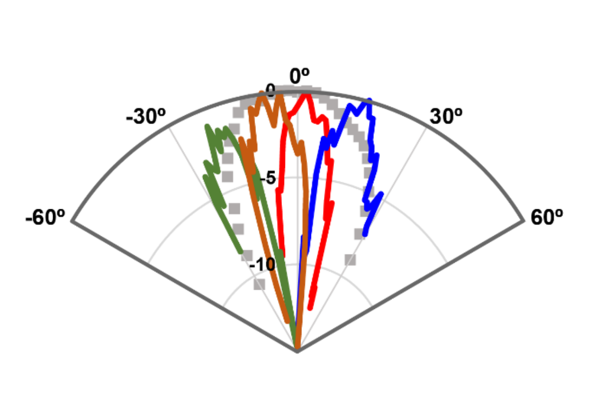


Fig. 6. Radiation Pattern of the phased-array.

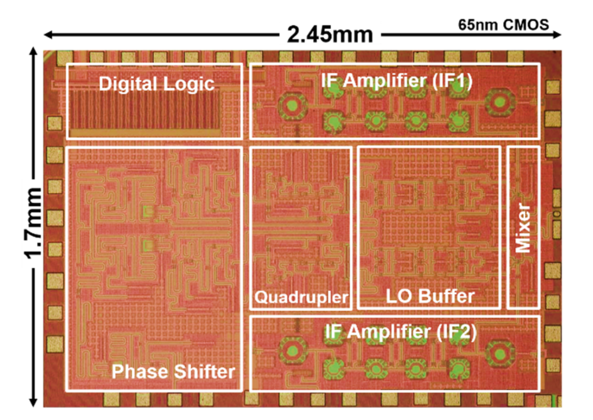


Fig. 7. Chip micrograph.

	[1],[6]	[3],[4]	[5]	[2]	This work
Tech. [nm]	65 CMOS	40 CMOS	40 CMOS	65 CMOS	65 CMOS
RF freq. [GHz]	240*	290*	252-279	278-304	242-280
Structure	Single-element	Single-element	Single-element	Single-element	Phased array
Architecture	Uni-directional	Uni-directional	Uni-directional	Uni-directional	Bi-directional
TX topology	Single stream tripler-last	Power combining	Power combining	Single stream mixer-last	Outphasing +Hartley
Max. baud rate [Gbaud]	TX: 8 RX: 8	TX: 21 RX: 14	TX: 28 RX: N/A	17	TX: 26 RX: 18
P_{DC} [W]	TX: 0.22 RX: 0.26	TX: 1.4 RX: 0.65	TX: 0.89 RX: 0.9	TX: 0.27 RX: 0.14	TX: 0.75 RX: 0.75
Area [mm^2]	TX: 2 RX: 2	TX: 5.19 RX: 3.15	TRX: 11	TX: 1.9 RX: 1.9	TRX: 4.17

*Center frequency

Fig. 8. Performance comparison of transceivers that operate above 200GHz.

Okada Laboratory

A CMOS Ka-Band SATCOM Transceiver with ACI-Cancellation Enhanced Dual-Channel Low-NF Wide-Dynamic-Range RX and High-Linearity TX

The satellite communication (SATCOM) has become a key technology for providing interactive TV and broadband internet services in low-density rural area. The non-line-of-sight (NLOS) on-the-move (OTM) communication using satellite has also been developed substantially. The Ka-band SATCOM in silicon is a promising solution due to wide available bandwidth, global coverage and low cost, especially in CMOS. In order to make use of satellite network as much as possible, multiple duplexing methods of polarization duplexing and frequency duplexing can be used together. In this paper, we present a Ka-band SATCOM transceiver chip based on direct-conversion architecture with high-linearity TX and dual-channel multi-mode RX. An adjacent channel interference (ACI) cancellation scheme is proposed to enhance the RX dynamic range. The SATCOM transceiver is fabricated in a 65-nm CMOS process.

Fig. 9 shows the proposed Ka-band SATCOM transceiver block diagram. The transceiver is composed of one 29-GHz transmitter and two 19-GHz receivers for dual channel communication as well as ACI cancellation in frequency duplexing mode. Both the transmitter and the receiver are in direct-conversion architecture with differential analog baseband. The transmitter includes a pair of R-C low-pass filters, a

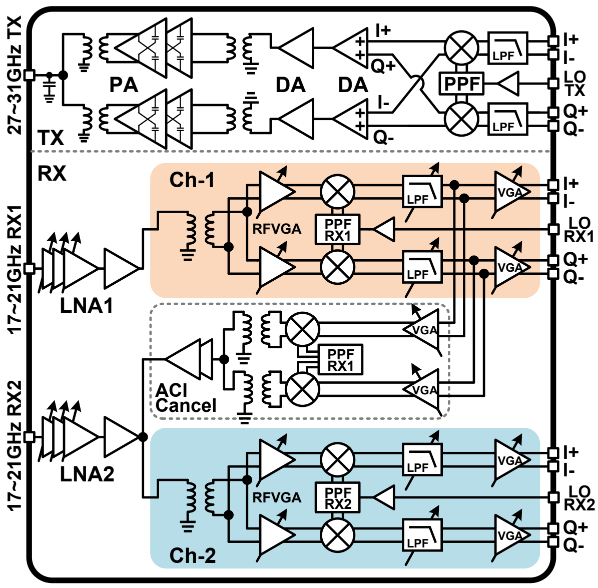


Fig. 9. Proposed Ka-band SATCOM transceiver block diagram.

double-balanced mixer, two stages of drive amplifier (DA) and a four-way two-stage power-combining power amplifier (PA) using the capacitive neutralization technique. The PA power combiner adopts transformer with 1:1 turn ratio for achieving high-quality factor and high coupling coefficient at millimeter-wave frequency. The TX LO is generated by using a poly-phase filter (PPF) from an external LO input. On the receiver side, the received 19-GHz RF signal is amplified with a three-stage low-noise amplifier (LNA) followed by an RF-amplifier and an RF-variable-gain amplifier (VGA). Both the LNA and the RF-VGA are designed with switched gain control. The RF signal is down-converted to baseband

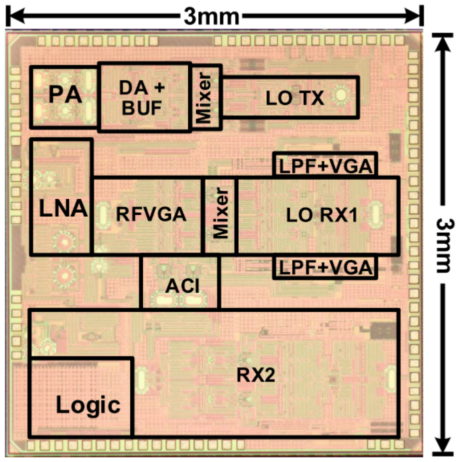
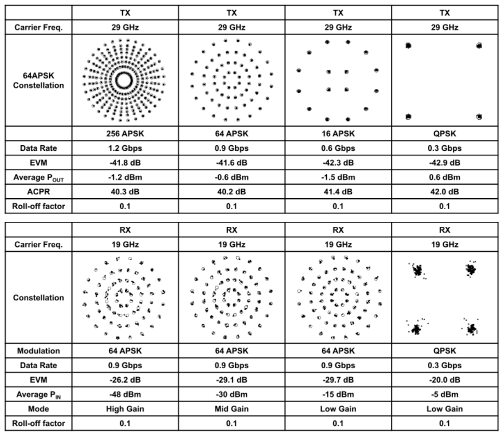


Fig. 10. Chip die micrograph.



	TX	TX	TX	TX
Carrier Freq.	29 GHz	29 GHz	29 GHz	29 GHz
64APSK Constellation				
	256 APSK	64 APSK	16 APSK	QPSK
Data Rate	1.2 Gbps	0.9 Gbps	0.6 Gbps	0.3 Gbps
EVM	-41.8 dB	-41.6 dB	-42.3 dB	-42.9 dB
Average P_{OUT}	-1.2 dBm	-0.6 dBm	-1.5 dBm	0.6 dBm
ACPR	40.3 dB	40.2 dB	41.4 dB	42.0 dB
Roll-off factor	0.1	0.1	0.1	0.1

	RX	RX	RX	RX
Carrier Freq.	19 GHz	19 GHz	19 GHz	19 GHz
Constellation				
Modulation	64 APSK	64 APSK	64 APSK	QPSK
Data Rate	0.9 Gbps	0.9 Gbps	0.9 Gbps	0.3 Gbps
EVM	-26.2 dB	-29.1 dB	-29.7 dB	-20.0 dB
Average P_{IN}	-48 dBm	-30 dBm	-15 dBm	-5 dBm
Mode	High Gain	Mid Gain	Low Gain	Low Gain
Roll-off factor	0.1	0.1	0.1	0.1

Fig. 11. Measured TRX constellation summary.

through a double-balanced mixer. PPF and external LO are also used for the LO generation in RX.

Fig. 10 shows the chip micrograph, which is fabricated in a 65nm CMOS process. The chip area is 9 mm^2, and it consumes 0.50 W in TX mode 0.58 W in dual-RX mode. The RF blocks use 1.05 V supply, the analog baseband use 1.2 V supply.

Fig. 11 shows the measured TRX performance with modulation signals of QPSK, 32APSK, 64APSK and 256APSK. Modulation schemes regulated in SATCOM standard DVB-S2X are included in the measurement. With a symbol rate of 150 MBaud, the TX achieves the best EVM of more than -40 dB. The roll-off factor is 0.1, and the measured ACPR is above 40dB. The measured RX EVM against the input power are measured with three different gain states. At low gain mode, the RX achieves an EVM of -29.7 dB with -15dBm input power under 64APSK modulation. For QPSK, the RX achieves an EVM of -20dB with -5dBm input power. The RX EVM is limited by non-linearity at high input power range.

Fig. 12 summarizes the SATCOM TRX performance, this study presents a high-linearity low-NF Ka-band CMOS SATCOM transceiver for earth ground platform. The proposed transceiver adopts dual-channel RX for multiple duplexing mode operation. Variable gain stages are distributed in RF and analog stages for wide dynamic range. Low-loss power combining network is employed in TX design. The transceiver is evaluated by modulation signal regulated in SATCOM standard DVB-S2X.

	This work	RFIC18 [3]	[6]	[7]	RFIC17 [8]	ISSCC18 [9]
Process	65nm CMOS	45nm CMOS SOI	GaAs discrete	GaAs+CMOS discrete	28nm CMOS	28nm CMOS
Application	SATCOM	SATCOM	SATCOM	SATCOM	5G	5G
Architecture	Direct Conversion	Super Heterodyne Digital IF	Super Heterodyne	Super Heterodyne	Direct Conversion	Super Heterodyne
Integration Level	RF+BB	RF+BB	RF	RF+BB+LO	RF+BB	RF
Elements	1TX+2RX	1TX+1RX	1TX+1RX	1TX+1RX	8TX+8RX	4TX+4RX
Operating Band (GHz)	TX: 27- 31	TX: 42- 47	TX: 27- 31	TX:27.2- 31.2	TX: 25.8- 28.0	TX:25.0- 31.0
	RX: 17- 21	RX:20- 22	RX:17- 21	RX:17.2- 21.2	RX: 25.8- 28.0	RX:26.5- 29.5
Roll-off factor	0.1	N/A	N/A	N/A	N/A	N/A
Ch. Bandwidth(GHz)	0.6	0.6	4	0.1	0.5	0.4
RX Gain Range (dB)	47 (-15 to 32)	14 (3 to 17) **	0	30 (7 to 37)	39 (30 to 69)	24 (10 to 34)
RX NF (dB)	5.0	8.0 **	3.5	4.0	6.7	4.7
RX IIP3 (dBm)	0.2	N/A	N/A	-3.5	-25.8	N/A
RX IIP2 (dBm)	37.3	N/A	N/A	N/A	N/A	N/A
ACI Cancellation (dB)	10.4	N/A	N/A	N/A	N/A	N/A
TX Psat (dBm)	19	>23	21.5	21	10.5	14
TX Pout@2%EVM (dBm)	10.6@QPSK 7.5@64APSK	N/A	N/A	N/A	-18*	6.7@QPSK** 5.3@64QAM**
TX ACPR@2%EVM (dB)	42.9@QPSK 40.2@64APSK	N/A	N/A	N/A	31.6	N/A
Supply Voltage (V)	1.05 / 1.2	1 / 1.8 / 3	4	5 / 4 / 1.3	1.05	1
PDC (W)	TX: 0.5	2.82	3.2	TX: 4.0	TX: 0.7	TX: 0.36
	RX: 0.58			RX: 3.3	RX: 0.4	RX: 0.17
Area (mm^2)	9	28.4	47 (6 chips)	207*** (9 chips)	7.28	27.8

*Calculated from TX EIRP ** Estimated in figure *** Including package

Fig. 12. Performance comparison of Ka-band mm-wave transceivers for SATCOM, 5G, and beyond.

Fukawa Laboratory

Home page: http://www.radio.ce.titech.ac.jp

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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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He received the B.E. degree from Department of Control Engineering and the M.E. degree from Department of Electrical Control Engineering, National Chiao Tung University, Hsinchu, R.O.C. (Taiwan), in 1997 and 1999, respectively, and another M.E. and the D.E. degree from Electrical and Electronic Engineering Department, Tokyo Institute of Technology, Tokyo, Japan, in 2007 and 2011, respectively. He served in Industrial Technology Research Institute (ITRI), Hsinchu, R.O.C. (Taiwan), from 2000 to 2005. He has been with Tokyo Institute of Technology from 2011 as a research fellow. Since April of 2016, he has been an Assistant Professor of Tokyo Institute of Technology. His research interests include multi-user MIMO systems, user scheduling algorithm, MIMO sounder, wireless sendor networks, and millimeter wave wireless systems. He is a member of IEICE and received the Best Paper Award of IEICE Communications Society in 2013

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
  - ✓ Eigenmode 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 cochannel 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

In-House Simulator Design & Implementation

FPGA on-board system simulators

4x4 MIMO fading simulators

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

Fukawa Laboratory

Multiuser Detection of Collided AIS Packets with Accurate Estimates of Doppler Frequencies [6], [10], [18], [21], [22]

Initially, the automatic identification system (AIS) aims at ship-to-ship or ship-to-coast wireless communications. To enhance AIS, Japan Aerospace Exploration Agency (JAXA) has employed satellites to observe AIS signals that are transmitted from ships across the open ocean. However, conventional and simple detection schemes cannot always operate well, because the wide coverage of the satellites causes frequent collisions of several AIS signal packets. To cope with such a problem, a multiuser detection scheme such as parallel interference cancellation (PIC) has been used for the signal detection. However, the bit error rate (BER) performance is degraded when channel parameters such as Doppler frequencies are estimated by the correlation between the received signals and the known training sequence. To alleviate the degradation, we propose to employ a highly accurate estimation scheme based on the quasi-Newton method for Doppler frequencies that affect the BER performance most seriously.

procedure OPTIMIZER
  $\mathbf{f}_{d_1} \leftarrow \hat{\mathbf{f}}_{d\ \mathrm{CD}}$
  $\mathbf{H}_1 \leftarrow \mathbf{I}$
  for $l = 1$ **to** *MaxIterations* **do**
    if $|\nabla\,\mathrm{PM}\left(\mathbf{f}_{d_l}\right)| \approx 0$ **then**
      return $\mathbf{f}_{d_l}$
    end if
    $\Delta\mathbf{f}_{d_l} \leftarrow -\alpha \cdot \mathbf{H}_l \cdot \nabla\,\mathrm{PM}(\mathbf{f}_{d_l})$.
    $\mathbf{f}_{d_{l+1}} \leftarrow \mathbf{f}_{d_l} + \Delta\mathbf{f}_{d_l}$
    $\mathbf{y}_l \leftarrow \nabla\,\mathrm{PM}(\mathbf{f}_{d_{l+1}}) - \nabla\,\mathrm{PM}(\mathbf{f}_{d_l})$
    $\mathbf{H}_{l+1} \leftarrow \left(\mathbf{I} - \frac{\mathbf{y}_l \Delta\mathbf{f}_{d_l}{}^{\mathrm{T}}}{\mathbf{y}_l{}^{\mathrm{T}} \Delta\mathbf{f}_{d_l}}\right)^{\mathrm{T}} \cdot \mathbf{H}_l \cdot \left(\mathbf{I} - \frac{\mathbf{y}_l \Delta\mathbf{f}_{d_l}{}^{\mathrm{T}}}{\mathbf{y}_l{}^{\mathrm{T}} \Delta\mathbf{f}_{d_l}}\right) + \frac{\Delta\mathbf{f}_{d_l} \Delta\mathbf{f}_{d_l}{}^{\mathrm{T}}}{\mathbf{y}_l{}^{\mathrm{T}} \Delta\mathbf{f}_{d_l}}$
  end for
  return $\mathbf{f}_{d_l}$
end procedure

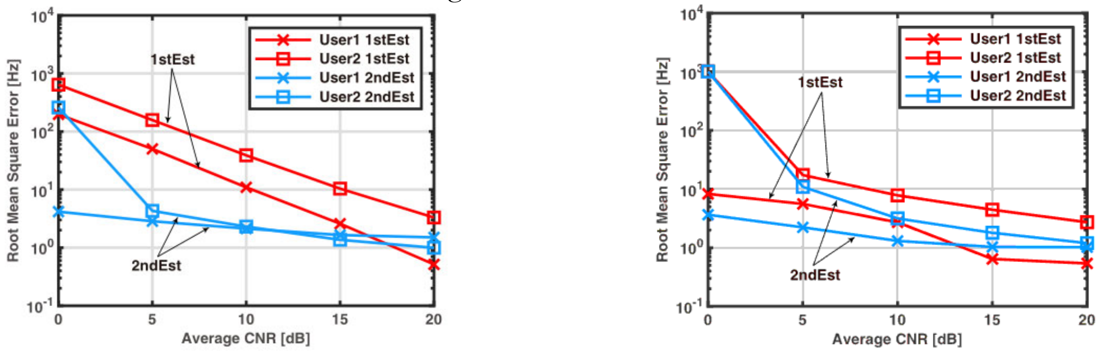
Algorithm 1. Quasi-Newton method

Quasi-Newton method is employed to improve the accuracy of the estimates of the Doppler frequencies. It aims to minimize the minimum path metric at a certain symbol timing, which is indicated by PM. At first, let $\mathbf{f}_d = [f_{d1}, \dots, f_{dK}]^{\mathrm{T}}$ where $(\cdot)^{\mathrm{T}}$ denotes transpose. In addition, let $\hat{\mathbf{f}}_d$ be the optimal estimate of $\mathbf{f}_d$ by the proposed method. Therefore, $\hat{\mathbf{f}}_d$ can be expressed as $\hat{\mathbf{f}}_d = \underset{\mathbf{f}_d}{\mathrm{argmin}}\ \mathrm{PM}$. Since PM represents a sum of the squared differences between the received and replica signals, $\hat{\mathbf{f}}_d$ is expected to become closer to the true values than the initial estimates using correlation detection (CD).

The proposed quasi-Newton method employs Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithm as the optimization scheme. This scheme can reduce an amount of computational complexity to calculate the inverse Hessian, because BFGS algorithm can approximate the inverse Hessian. Furthermore, the quasi-Newton method is superlinearly convergent and thus requires fewer iterations for convergence. **Algorithm 1** lists the procedure of the quasi-Newton method, in which l is the index of iterations, $MaxIterations$ is the maximum number of iterations, $\hat{\mathbf{f}}_{d\ \mathrm{CD}}$ is the estimate of $\mathbf{f}_d$ by CD and set to the initial value, $\mathbf{H}_l$ denotes the approximated inverse of Hessian, α is the step size, $\nabla\mathrm{PM}(\mathbf{f}_{dl})$ is an approximated gradient of PM with respect to $\mathbf{f}_{dl}$, and $\mathbf{I}$ is the identity matrix.

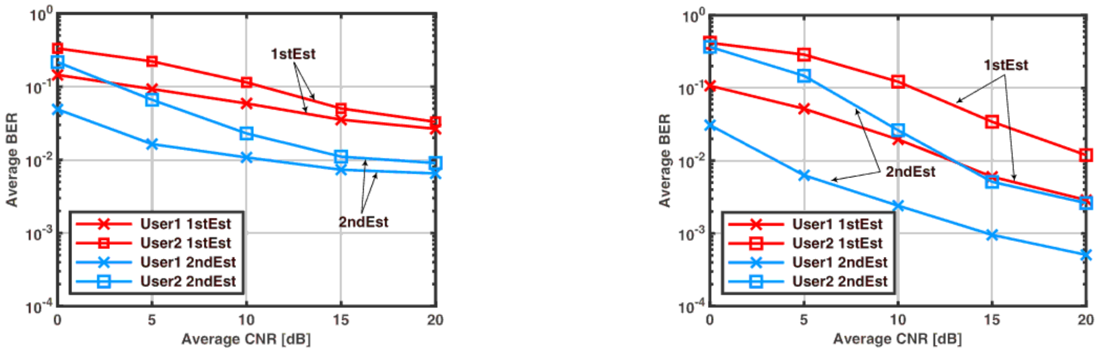
The estimation error of the Doppler frequencies was evaluated as the root mean square error (RMSE). Figs. 1(a) and (b) show the RMSE when desired to undesired signal power ratio (DUR) was set to 6 dB and 10 dB, respectively. In addition, “1stEst” and “2ndEst” indicate the RMSEs of the initial (first) estimation using CD and the updated (second) estimation using the proposed scheme, respectively. It can be seen from the figures that the quasi-Newton method can improve the accuracy of the Doppler frequency estimation, except that RMSE of 2ndEst of user 1 is a little worse than RMSE of 1stEst of user 1 when the average CNR is greater than 15 dB.

Figs. 2(a) and (b) show the average BER performance when DUR was set to 6 dB and 10 dB, respectively. It is seen that the proposed scheme can improve the BER performance more drastically than the initial parameter estimation using CD. In particular, the average BER of user 1 can achieve 1×10^{-2} when DUR is 6 dB and the average CNR is 10 dB.



(a) DUR 6 dB (b) DUR 10 dB

Fig. 1. RMSE of Doppler frequency



(a) DUR 6 dB (b) DUR 10 dB

Fig. 2. Average BER

Distributed Inter-cell Interference Coordination for Small Cell Wireless Communications: A Multi-Agent Deep Q-Learning Approach [2], [15], [19]

Dense deployment of small cell multiple-input multiple-output (MIMO) systems can potentially improve the system capacity. Meanwhile, overlapping of neighborhood cell can increase inter-cell interference (ICI), and further lead to system capacity degradation. Traditional approach of ICI optimization conducts exhaustive search (ES) on transmit power levels and beamforming vectors from a pre-defined codebook, which makes computational complexity grow exponentially with the number of BSs. To solve this problem, an independent deep Q-learning (IDQL) is proposed, which can control both the transmit power and beamforming in a distributed manner.

Fig. 3 shows the system model of 3 BSs communicate with 3 user terminals (UTs). Each BS and UT are equipped with N and M, respectively, transmit and receive antennas. According to the following system model, we can form received signal model as

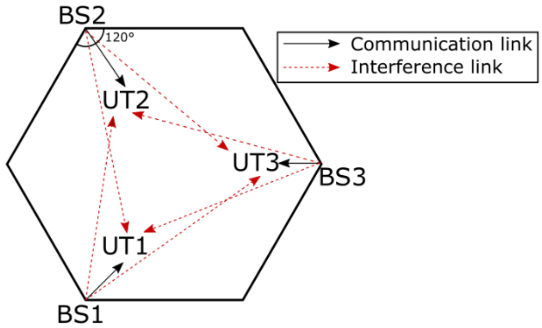


Fig. 3. A block diagram of HB massive MIMO transmitter and receiver.

$$\sqrt{p_i}\hat{s}_i = \frac{\mathbf{g}_{i,i}^{\mathrm{H}}}{\| \mathbf{g}_{i,i} \|^2}\{\sqrt{p_i}\mathbf{g}_{i,i}s_i + \sum_{j=1, j\neq i}^{K}\sqrt{p_j}\mathbf{g}_{i,j}s_j + \mathbf{n}_i\}$$

$\mathbf{g}_{i,j} = \mathbf{H}_{i,j}\mathbf{f}_j$ denotes M-by-1 equivalent channel vector between the i-th UT and the j-th BS. Thus, the SINR of the i-th UT is given by

$$\mathrm{SINR}_i = \frac{p_i \| \mathbf{g}_{i,i} \|^4}{\sigma_n^2 \| \mathbf{g}_{i,i} \|^2 + \sum_{j=1, j\neq i}^{K} p_j |\mathbf{g}_{i,i}^{\mathrm{H}}\mathbf{g}_{i,j}|^2}$$

Given predefined codebooks $\mathbb{P}$ for transmit power levels and $\mathbb{F}$ for beamforming vectors, the optimization problem $\mathcal{P}$ is to maximize the average system capacity and is formulated as

$$\begin{aligned} \mathcal{P}: &\max \ C \\ &\mathrm{s.t.}\ \mathbf{f}_k \in \mathbb{F}, \forall k \in [1, K], \text{and} \\ &\quad p_k \in \mathbb{P}, \forall k \in [1, K]. \end{aligned}$$

In the proposed IDQL, the state of the environment $\boldsymbol{s} \in \mathbb{R}^{K^2|\mathbb{F}|\times 1}$ is set as followed:

$$\mathbf{x}_{i,j} = [\| \mathbf{g}_{i,j}(\mathbb{F}_1) \|^2, \dots, \| \mathbf{g}_{i,j}(\mathbb{F}_{|\mathbb{F}|}) \|^2]^{\mathrm{T}}$$

$$\mathbf{s} = [\mathbf{x}_{1,1}^{\mathrm{T}}, \dots, \mathbf{x}_{1,K}^{\mathrm{T}}, \dots, \mathbf{x}_{K,K}^{\mathrm{T}}]^{\mathrm{T}}$$

where $|\mathbb{F}|$ is the cardinality of set $\mathbb{F}$, and $\mathbf{g}_{i,j}(\mathbb{F}_f)$ denotes the equivalent channel vector including the selected f-th beamforming vector. The action set $\mathcal{A}$ consists of $|\mathbb{P}| \times |\mathbb{F}|$ elements correspond to all the possible combinations of transmit power levels and beamforming vectors. The reward r is set to the average system capacity.

Simulation result shows that the training process of the proposed IDQL-based scheme converges with several policies, where the maximum number of iterations is 100. Fig. 4 shows the cumulative density functions (CDFs) of the system capacity obtained by the proposed IDQL-based and the conventional schemes. The decreasing ε-greedy policy was employed during the training process of the IDQL-based scheme. It shows that the IDQL-based scheme achieves 8.91 bps/Hz at CDF of 0.5, which is 82% and 90% of those of the ES and supervised deep learning (SDL) schemes, respectively, in spite of not using any training data.

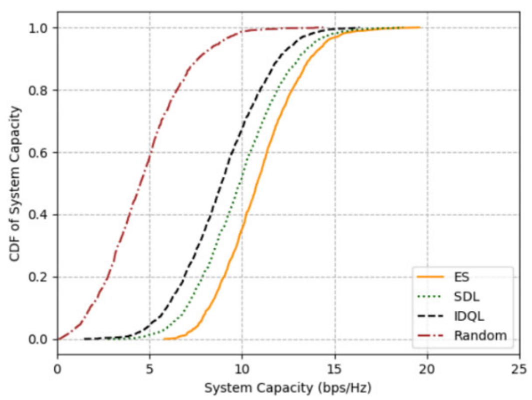


Fig. 4. CDF of the system capacity of several schemes

Input: Number of iterations I, number of episodes E, number of BSs K, and ε
Output: solution of (8) by DQL agents
1: **Initialize** weight vector $\mathbf{w}$ of Q-networks randomly
2: **for** (iteration $= 1$, iteration $\leq I$, iteration++){
//Stage 1: collecting data
3: Clear memory buffers of all agents
4: **for** (episode $= 1$, episode $\leq E$, episode++){
5: Generate channel instance $\{\mathbf{H}_{i,j}\}$ of (2)
6: Obtain state $\mathbf{s}$ of (15)
7: Normalize $\mathbf{s}$ into $\tilde{\mathbf{s}}$
8: **for** (agent(j) $= 1$, agent $\leq K$, agent++){
9: Select agent's action a_j by (17) with ε
10: Obtain y from (16) and (7) with $\{\mathbf{H}_{i,j}\}$ and collected actions $\{a_1, \dots, a_K\}$
11: The j-th agent stores $\{\tilde{\mathbf{s}}, a_j, y\}$ into its memory
}
12: Decrease ε for exploitation (optional)
}
//Stage 2: updating the Q-network
13: **for** (agent $= 1$, agent $\leq K$, agent++){
14: Train the agent's Q-network by (14) with saved data
}
//Stage 3: evaluating performance
15: Repeat lines from 5 to 11 with $\varepsilon = 0$, where y is collected only in line 11
16: Compute the average of y that are collected in line 15 to evaluate performance of the agents.
}

Algorithm 2. IDQL-based ICI

Adaptive Channel Prediction for Hybrid Beamforming over Time-Varying Massive MIMO Channels [3], [17], [23], [24]

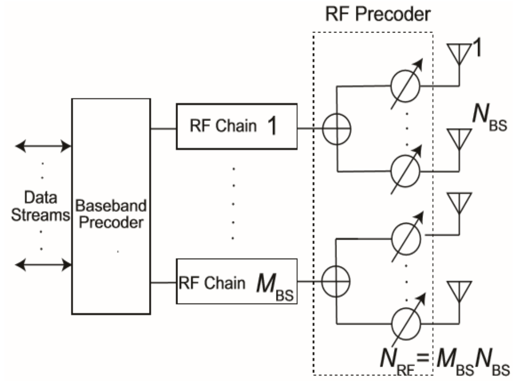


Fig. 5. A block diagram of HB massive MIMO transmitter and receiver.

MIMO have been employed in 4G systems, and also plays a very important role in the 5th generation mobile communications (5G) and 5G beyond. To implement the massive MIMO, hybrid beamforming (HB) is one of the most promising techniques for reducing the cost, because HB is composed of the analog beamforming (AB) and the digital beamforming (DB) and thus can decrease the number of baseband and radio frequency (RF) circuits significantly.

For time division duplex (TDD) massive MIMO communications, an adaptive prediction is proposed for downlink (DL) time-variant channels, which is based on the estimation result of the uplink (UL) channel.

The considered HB massive MIMO system model is shown in Fig. 5. It shows a block diagram of an HB massive MIMO transmitter and receiver at the base station (BS), in where the BS is equipped with N_{RF} (> 100) antenna elements and M_{BS} RF chains, and communicates with K user equipments (UEs).

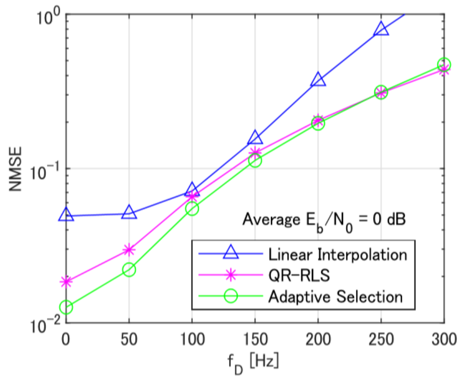


Fig. 6. NMSE of DL channel prediction.

Each UE has N_{UE} antennas and one RF chain per antenna element. Although time-variant frequency selective fading channels are assumed, this paper focuses on one subcarrier of OFDM and its channel can be regarded as flat fading.

The proposed scheme approximates the UL channel vector of one data stream as a weighted sum of array response vectors, and selects one result from those of the following two methods to predict the weights of the UL channels: One linearly interpolates weight coefficients that are estimated by using training signals, while the other employs QR-recursive least squares (RLS) with the detected data in order to track equivalent channels. The criterion of selection is a sum of the squared minimum distances between minimum mean square error (MMSE) detector's outputs and candidate constellations of transmitted signals during two data frames. Thus, the selected channels are given by

$$\arg\min_{\tilde{\mathbf{H}}_{\mathrm{HB}}}\left[\sum_{k=1}^{K}\sum_{q=1}^{N_{UE}}\left\{\sum_{m=N_{TR}+1}^{N_{TR}+N_D}\left(\min_{s\in S}\left|\tilde{r}_{k,q}(m)-s^2\right|\right)+\sum_{m=2N_{TR}+N_D+1}^{2N_{TR}+2N_D}\left(\min_{s\in S}\left|\tilde{r}_{k,q}(m)-s^2\right|\right)\right\}\right]$$

where $\tilde{\mathbf{H}}_{\mathrm{HB}}$ represents the estimated channel matrices, S is a set of constellations s, and $\tilde{r}_{k,q}(m)$ is the m-th MMSE detector's output corresponding to the q-th $(1 \le q \le N_{UE})$ data stream of the k-th $(1 \le k \le K)$ UE. In addition, the UL packets is assumed to consist of two slots and each slot is composed of N_{D} data signals following N_{TR} training signals.

Simulation results are shown in Fig. 6, which shows the normalized MSE of the DL channel prediction using linear extrapolation of the selected UL channel estimate. When the maximum Doppler frequency is less than 150 Hz, it can be seen that adaptive selection can improve the accuracy of the DL channel prediction.

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.

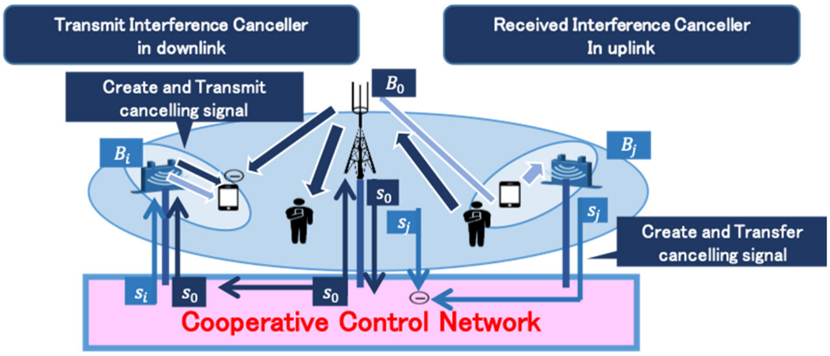
Recent Research Topics

- **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 [5][7][11]

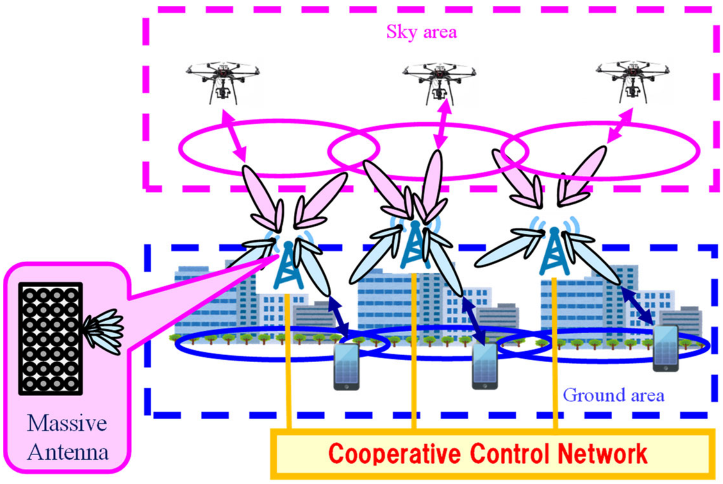
In the three-dimensional(3D) layered cell construction in same frequency bands are used in both macro and small cells, we pioneered interference cancellation technology using “cooperation control network” where each cell cooperates through a network ahead, for LTE and 5th generation mobile communications. 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 [4][6][12]

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.



Okumura Laboratory

Visiting Professor Yukihiko Okumura

Prof. Okumura received his M.S. degree in electrical engineering from the Tokyo University of Science, Tokyo, Japan, in 1991, and his Ph.D. degree in engineering from the Tohoku University, Miyagi, Japan, in 2006. Since 1992, he has been engaged in the research, standardization and development of wideband/broadband mobile radio communication technologies, terminals and systems, at NTT DOCOMO, INC., Kanagawa, Japan, and is currently engaged in the development of 5G commercial mobile terminals and is promoting field trials of various 5G solutions, at DOCOMO Technology, Inc., Kanagawa, Japan. He is a Leader of 5G Trial Promotion Group, the Fifth Generation Mobile Communications Promotion (5GMF) since 2016. He is a senior member of The Institute of Electrical and Electronics Engineers, Incorporated (IEEE).

Research Interests

The fifth-generation mobile communication system (5G) is expanding rapidly since commercial service started in March 2020, to accommodate both rapid growing of mobile data traffic due to the spread of smartphone/tablets and qualitative change of data traffic caused by the spread of IoT (Internet of Things), (1) dramatic improvement of the system capability, (2) higher bit rates of data communication, (3) drastic increase of the number of connected devices, (4) larger reduction of power consumption, and (5) reduced cost of radio access network and mobile terminals, are required compared for 4G. Moreover, in order to flexibly allow new mobile services and applications that needs from various industries create, further enhancement of 5G and consecutive research of next-generation mobile communication system where novel radio access technologies can be introduced in phased approach are needed.

Okumura laboratory focuses on the flowing research topics:

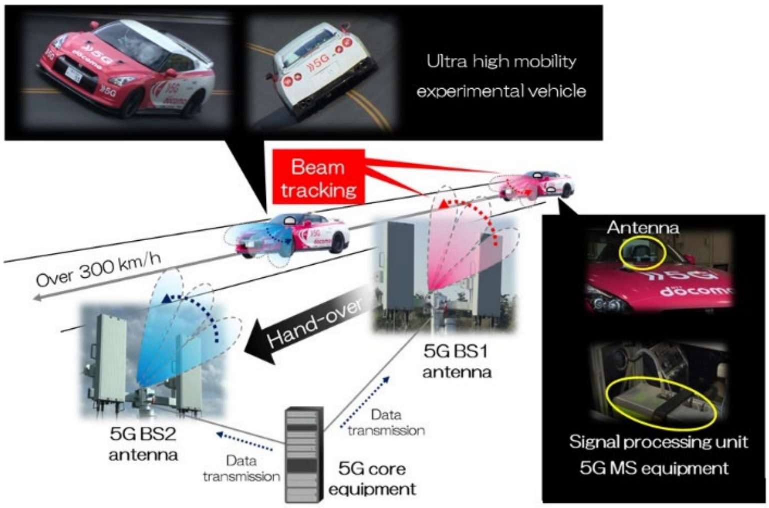
- ✓ ***Proposal and performance evaluation of radio access system for next-generation mobile communication system***
- ✓ ***Radio access technologies for further enhancement of next-generation mobile communication system***
- ✓ ***Radio control technologies and mobile services and applications for further enhancement of next-generation mobile communication system***

In addition to computer simulations etc. on above research topics, practical studies toward actualization of new mobile solutions are promoted, and students can tackle a variety of researches in the state-of-the-art corporate research and development environment.

Recent Research Topics

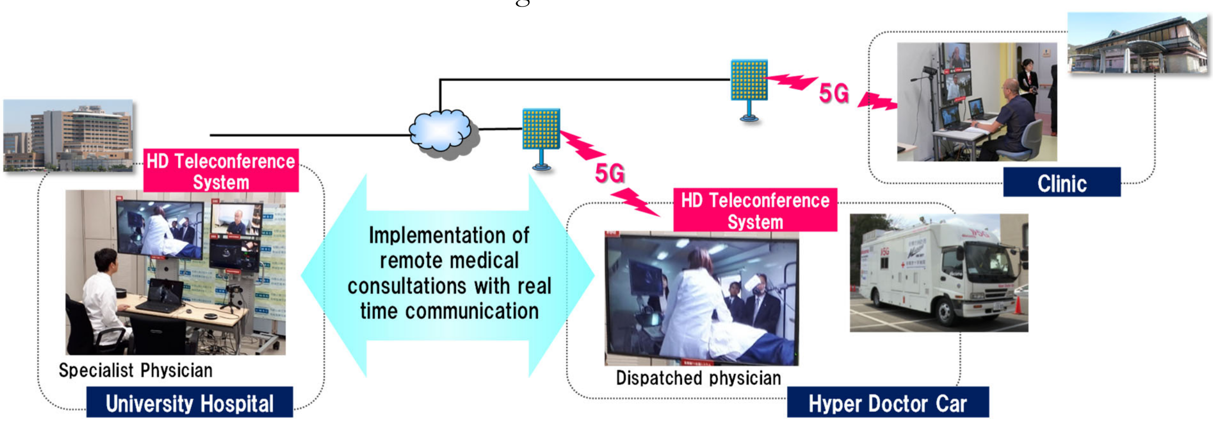
5G Communication Experiment with Ultra High Mobility

In order to support ultra-high mobility on a bullet train, we have conducted an outdoor experimental trial using the specially customized vehicle with the velocity of up to 300 km/h. This figure shows appearances of the base station (BS) and the mobile station (MS) of the 5G prototypes, respectively. The experimental trial employs two BS antennas with Massive MIMO and performs hand-over experiment between two BSs. We were world-first successful of following four experiments to verify possibility of receiving 5G service in super high-speed mobile environments: (1) 5G data transmission in maximum speed of 305 km/h, (2) downlink 5G transmission achieves 1.1 Gbps throughput in ultra-high speed of 293 km/h, (3) hand-over between two BSs under 290 km/h condition, (4) uplink 5G transmission of 4K high frame-rate live stream from vehicle under 200 km/h.



5G System Trials of Use-cases to Solve Social Problems

As an example of activity to create new mobile solutions, there is field trial conducted in Wakayama Prefecture in January 2020, which has been continued since 2018 with the aim of mitigating the problem of the unequal level of medical care in metropolitan and regional areas through advanced telemedicine consultations. At 2020, utilizing 4.5 GHz frequency band 5G radio device was used to transmit viewings of highly medical equipment installed in "hyper doctor car", in which high level medical consultations and treatment could be conducted. It was confirmed that consultations could be held when specialists were able to connect with mobile clinic vehicles or clinics at a remote location via HD video on a 5G network, consultations that felt as if the university hospital physician was sitting right in front of the patient through said HD video transmitted via 5G, with participants commenting that these consultations provided a much higher level of quality than those they had previously. This trial confirmed that an even higher quality of consultation could be performed using a mobile clinic vehicle, which is expected to raise the level of medical consultations that can be provided in locations such those located in remote mountainous regions.



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