Mobile Communications Research Group
Tokyo Institute of Technology

2019

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 (http://www.ap.ide.titech.ac.jp)

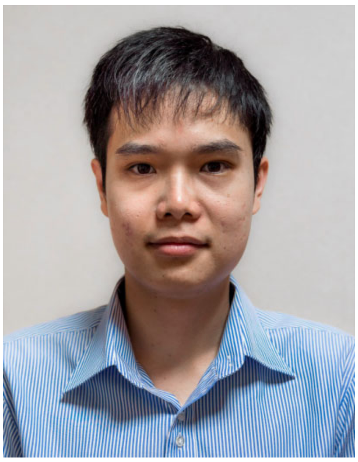
Professor Jun-ichi Takada

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. From 1992 to 1994, he was a Research Associate at Chiba University. From 1994 to 2006, he was an Associate Professor at Tokyo Institute of Technology, where he has been a Professor since 2006. He is currently with the Department of Transdisciplinary Science and Engineering, School of Environment and Society. He was also a part time researcher in National Institute of Information and Communications Technology from 2003 to 2007. His current research interests are the radio wave propagation and channel modeling for various wireless systems, applied radio measurements and information technology for regional/rural development. He is fellow of IEICE, senior member of IEEE, and member of Japan Society for International Development (JASID).

Assistant Professor 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, and the best poster awards of IEICE RISING and SRW in 2019. 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 with first class honours from Sirindhorn International Institute of Technology, Thammasat University, Pathumthani, Thailand, in 2013, and the M.E. and D.E. degree 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 and Ilmenau University of Technology, Germany in 2016 and 2018, respectively. He received the best student presentation award of IEICE Short Range Wireless (SRW) conference in 2017, and best student paper award from IEEE Antennas and Propagation Society (APS) in 2019. 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 drones, underground railways, underwater wireless sensors, 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, T-matrix based scattering modeling, and the propagation prediction by machine learning. 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**
  - Experimental Investigation of Energy Detector and Matched Filtering For Spectrum Sharing at High-Frequency Band
  - Minimum Path Loss Prediction Method for Spectrum Sharing in mm-Wave Band
  - Software Defined Radio based Cellular Signal Measurement System to Construct Interference Map for Spectrum sharing
- **Radio Propagation Simulation and Environment Modeling Research**
  - Radio Propagation Loss Prediction by Artificial Neural Network
  - Prediction of Diffuse Scattering Characteristics by Physical Optics Approach in 32 GHz band
  - Moving Object Tracking by Stereo Cameras for Dynamic Radio Propagation Simulation
- **Channel Sounding and Radio Propagation Research**
  - Study on the Characteristics of the Radio Channel in Subway Tunnel
  - Identification of Scattering Objects for 11 GHz Urban Microcell Radio Channel via Visual Inspection
  - Development of Hand Motion Tracking System using Channel State Information from Wi-Fi Devices
  - Prediction Method of Shadowing Effect by Complex-shape Object in mm-Wave Band
  - Radio Wave Propagation for Underwater Wireless Sensor Networks (UWSNs) Deployment
  - Theoretical Method Based Rain Attenuation Prediction for Millimeter-Wave Radio in Tropical Region

Takada Laboratory

Experimental Investigation of Energy Detector and Matched Filtering For Spectrum Sharing at High-Frequency Band [14]

(Supported by the Ministry of Internal Affairs and Communications)

Because of the scarcity of spectrum caused by the rapid increase of wireless devices, especially at sub-6 GHz bands, the dynamic spectrum sharing (DSS) scheme at the high-frequency band has been widely utilized. In DSS, a robust detector to detect very weak signals is needed as the low-priority system (secondary system) may not be allowed to transmit if it significantly affects the high-priority system (primary system).

Therefore, this work investigated the performance of matched filter (MF) and energy detector (ED) at 17 GHz band through the wired connection between Tx (signal generator) and Rx (spectrum analyzer) and compared with that of theory. Fig. 2 shows the plot of signal to noise ratio (SNR) and the probability of detection (PD) at 10% false alarm rate. In the case of ED, the measured follows the theory, whereas the measured MF was few dBs worse than theoretical values. However, the MF had a higher performance since the signal with SNR as low as -30 dB could be detected with at least 90% detection rate, whereas with the same condition, the ED could only detect up to -16 dB

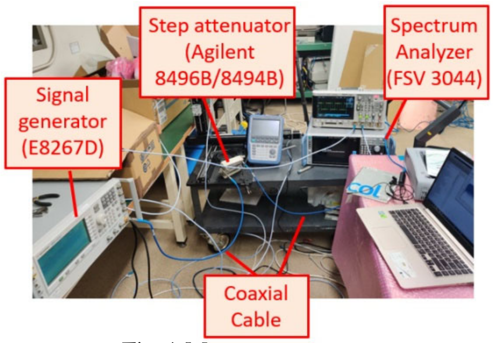


Fig. 1 Measurement setup

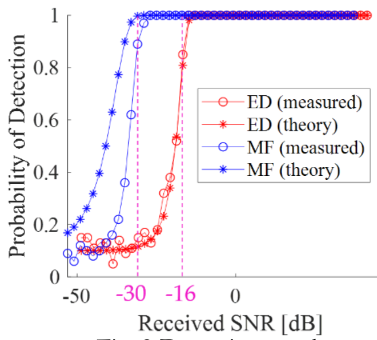


Fig. 2 Detection results

Minimum Path Loss Prediction Method for Spectrum Sharing in mm-Wave Band [15][23][34][37]

(Supported by the Ministry of Internal Affairs and Communications)

This research proposes a frequency resource detection method for spectrum sharing using the Kirchhoff approximation (KA) technique. KA is a well-known technique that can deal with the path over multiple buildings, which is the most dominant path in the suburban area. The proposed method utilized ordinary KA with building information and elevation profile considering blockage sensitivity of mm-Wave band. Moreover, the proposed model was designed to calculate minimum path loss by selecting only a few building edges (edge1 & edge2) that significantly block the line-of-sight (LOS) ray. Through this implementation, it is possible to limit the overestimation of the path loss while keeping the value bigger than free-space path loss (FSPL) to ensure the transmission opportunity of the secondary system. The spectrum detection accuracy of the proposed method, as well as vertical plane launching (VPL) and FSPL, are shown in Fig.2. The proposed method improved detection accuracy (TP+TN) for 7.5 % compared with VPL while reducing MD rate as 10%. Further reduction of MD rate can be considered as a future task as this rate is the biggest matter of concern for the primary system.

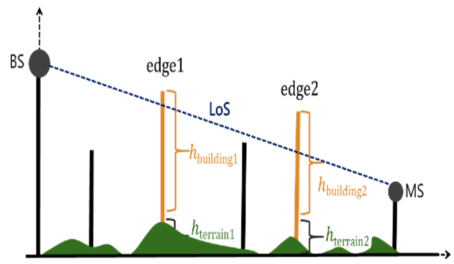


Fig. 1 Concept of proposed method

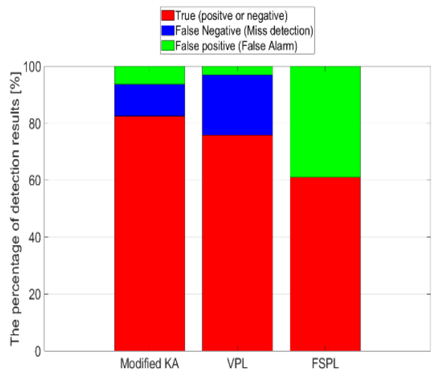


Fig. 2 Comparison of detection accuracy

Software Defined Radio based Cellular Signal Measurement System to Construct Interference Map for Spectrum sharing [21] [38]

(Supported by JSPS KAKENHI 19H02136)

Dynamic spectrum access (DSA) has been widely discussed to address the spectrum scarcity issue caused by the increased demand of the radio spectrum. In DSA, both primary and secondary systems should coexist without interfering with each other. This work considers the construction of measurement-based interference map using point to point channel measurement to study and model the interference in the DSA. For measurement, Software-defined radio (SDR) based receivers and the uplink cellular signal from commercial mobile router is considered. To monitor the transmit power variation of a mobile router (UE), one receiver (Rx1) is kept as a reference receiver very near to the mobile router. If another receiver (Rx2) placed at the location of interest is phase synchronized with reference receiver, correlation of received signals at both receivers are maintained, and channel gain can be calculated by selecting the signal length within coherence time.

Phase coherency between the received signals at two free-running bladeRF based SDR receivers was examined by feeding signal from the signal generator into two receivers, as shown in Fig. 2. After IQ imbalance correction, power calibration, and carrier offset compensation, the phase difference between signals received at two receivers was found to be correlated with phase coherency of 0.4 seconds. In the future, using this system point to point channel measurement and interference map over the whole area can be created.

Fig. 1 Concept of measurement system

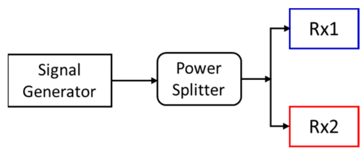


Fig. 2 Measurement setup

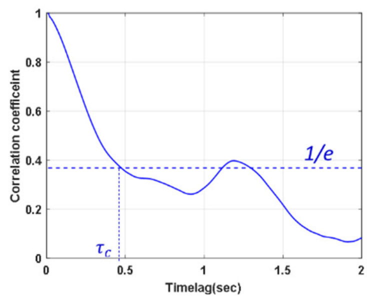


Fig. 3 Autocorrelation plot of phase difference

Radio Propagation Loss Prediction by Artificial Neural Network [9] [40] [41] [44] (Supported by the MIC SCOPE)

In recent years, wireless network systems are utilized in various industry fields, and the wireless service area planning became one of the important tasks to realize efficient and high-quality wireless communication service. The machine learning technology attracts the interests of researchers to improve the efficiency of the area planning task because the radio propagation loss in unknown locations can be predicted by the training data without explicit algorithms. Our previous work showed that the path loss (PL) characteristics become complicated in the high PL region, and it can degrade the entire prediction accuracy. In this work, we proposed the two-step PL prediction method by the artificial neural network (ANN) to solve the issue. Firstly, the area is classified into several zones according to the PL range. And then, the PL is predicted by ANNs that were trained for respective zones. Our proposal was evaluated by the ray-tracing simulation data, and the result showed that it improved the root mean square error (RMSE) of PL prediction from 7.9 dB to 4.1 dB. The method is expected to be utilized for the wireless service area planning in various environments.

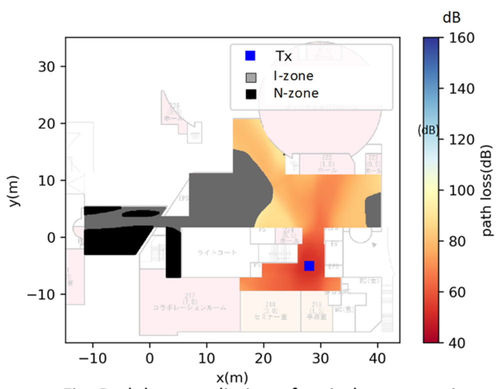


Fig. Path loss prediction of an indoor scenario

Tab. Summary of Prediction result

Simple regression		
	Classification	PL prediction RMSE
Total		8.6 dB
Two-step prediction (proposal)		
Region	Classification success rate	PL prediction RMSE
S-zone	0.99	2.8 dB
I-zone	0.81	8.2 dB
N-zone	0.88	14.1 dB
Total	0.95	4.4 dB

Takada Laboratory

Prediction of Radio Channel Characteristics by Physical Optics Approach in 32 GHz band [17]
(Supported by the MIC SCOPE)

As the start of the commercial service of the fifth-generation (5G) system, millimeter-wave wireless communication is expected to be more common in the mobile communication field. It is known that the diffuse scattering of the propagation wave becomes more severe in those high-frequency bands because the roughness and microscopic structure of the reflecting surface is not negligible compared to the wavelength of the wave. Therefore, understanding how the microscopic structures of the surface affect scattering characteristics is important to develop the prediction method of the propagation channel for the system performance evaluation. In this research, we conducted the diffuse scattering measurements in 32 GHz band by the virtual array-based channel sounder. We also calculated the propagation channel by the Physical Optics (PO) approach from the detailed three-dimensional environment model measured by the laser scanner. The result showed that the PO approach can predict the angular characteristics of the diffuse scattering quite accurately. Further investigation in various propagation scenarios is planned to clarify the feasibility of our prediction approach.

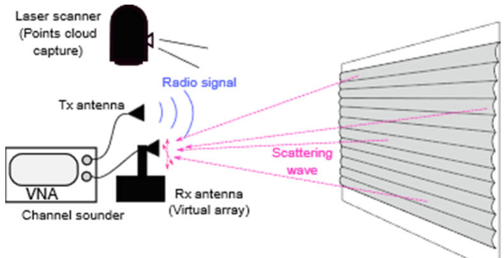


Fig. 1 Measurement Approach

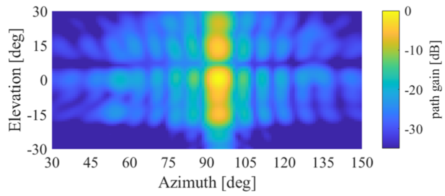


Fig. 2 Measurement result (window blind)

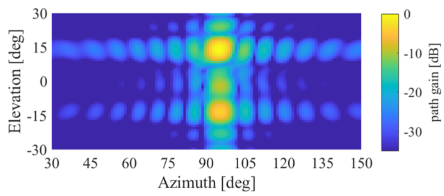
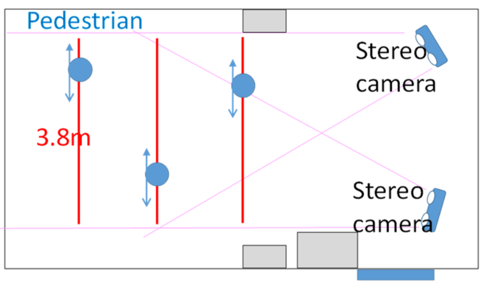


Fig. 3 Prediction result (window blind)

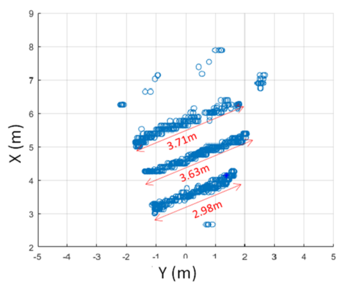
Moving Object Tracking by Stereo Cameras for Dynamic Radio Propagation Simulation
(Supported by the MIC SCOPE 185103006)

Because of the rapid progress of computer science technologies, radio propagation simulation technologies become essential to understand the propagation mechanism and to predict the channel characteristics. Although the ray-tracing has been widely used for the purpose, the precise 3D environment model is indispensable to obtain the accurate result. However, there is a difficulty in constructing the environment model in dynamic environments such as crowded indoor and intelligent transport systems (ITS) scenarios. In this research, we developed the measurement system to construct dynamic environment models by utilizing stereo cameras. Firstly, we prepared the static environment model without pedestrians by the laser scanner. And then, only the moving objects are detected by the stereo cameras in the actual dynamic environment. The dynamic environment model can be constructed by importing those moving objects into the static model.



(a) Measurement layout

(b) Camera view



(c) Object detection result

Fig. Pedestrian position detection experiment in an indoor office.

Study on the Characteristics of Radio Channel in Subway Tunnel [24]

Using radio communication for train control is more and more demanded. Especially in a subway, propagation of a radio wave characterizes by tunnel structure, and radio wave propagation has a large effect on the reliability of the train control. In this environment, multipath fading should be characterized accurately for the system design.

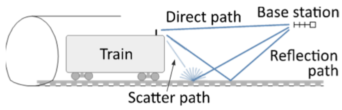


Fig.1 Basic radio wave propagation mechanism at subway tunnel

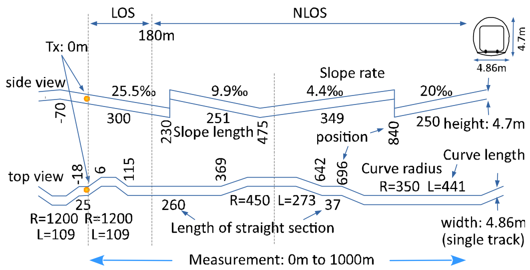


Fig.2 Measurement site, tunnel information

In the case of the radio wave propagation in a tunnel, the reflected wave which the wall brings about is considered to be a dominant propagation mechanism. To model the multipath fading, Nakagami-Rice distribution is often used to represent both line-of-sight (LOS) and non-line-of-sight (NLOS) conditions. Rician K-factor is the ratio of the dominant path power and scattered path power and represents the depth of multipath fading. Although the K-factor was evaluated in the 50-wavelength interval, except a less than 25-m short-range, K-factor is very small except for a few peaks, regardless of the existence of LOS condition.

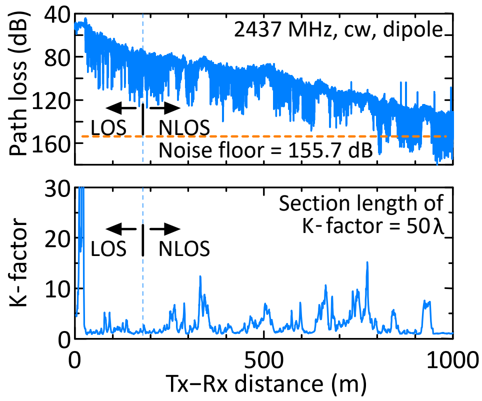


Fig.3 The distance characteristics of the Rician K-factor in a subway tunnel

Identification of Scattering Objects for 11 GHz Urban Microcell Radio Channel via Visual Inspection

Researches on mobile radio channel have revealed that if a pulse is transmitted from the transmit antenna (Tx) then several pulses are received at the receiver (Rx) due to the presence of the obstructing object between Tx and Rx.

An important parameter in wireless communication to characterize the propagation channel is the polarization. The cross-polarization indicates the polarization behavior of the propagation channel which means how vertically polarized signal is converted by the channel to horizontally polarized signal and vice-versa. Among these several pulses, the cross-polarization value is low or negative and power contribution is high. This means that there is depolarization due to the obstructing object (OO) in the environment. Deep changes of the propagation path characteristics such as additional path loss, spatial fading which decrease the performance of the mobile communication system may occur due to the presence of the OO. Before the transmitted signal has reached the Rx, an important part of the energy is lost due to the interaction between the signal and the obstruction objects. These interactions are commonly referred to as the propagation mechanism.

This study aims at understanding the governing mechanism of the non-line-of-sight propagation paths in the street microcell environment by identifying and characterizing the interacting objects.

Fig : Measurement area: urban microcell environment in Ishigaki, Japan at 11 GHz band

Takada Laboratory

Development of Hand Motion Tracking System using Channel State Information from Wi-Fi Devices [25]

Wi-Fi has been widely leveraged in non-intrusive RF hand motion sensing due to its low cost, ubiquitous, less privacy concern, and easy to deploy. Generally, hand motion information can be captured from channel state information (CSI) of Wi-Fi chips in terms of the Doppler shift. This research aims to trace a trajectory of hand gesture using the Doppler profile extracted from the Doppler spectrum of CSI. In practice, it is challenging to obtain the profile corresponding to hand motion because the Doppler spectrum captures the movement of entire human limb where each segment induces different magnitude of the Doppler shift. This results in the spread of the Doppler spectrum as shown in Fig. 1. By investigating the mechanism of limb motion with our simulation, the algorithm for extracting the hand-only Doppler profile was developed. In the experiment, the trajectory of the hand when performing the M-shape gesture were estimated from 6 Doppler profiles obtained from 3×2 MIMO Wi-Fi channel where the antennas were placed at different positions as shown in Fig. 2. The tracking results in both simulation and measurement could resemble the M-shape hand trajectory as depicted in Fig. 3.

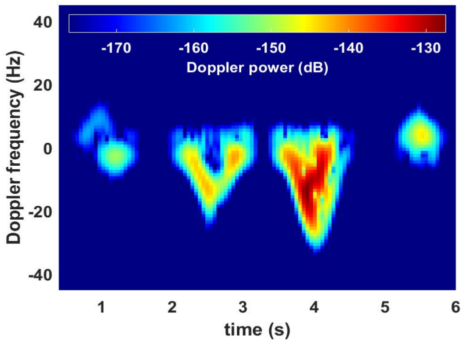


Fig. 1 Doppler spectrum of hand gesture

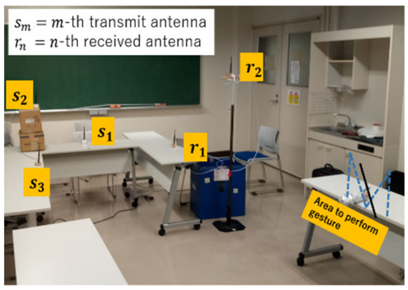


Fig. 2 Measurement scenario

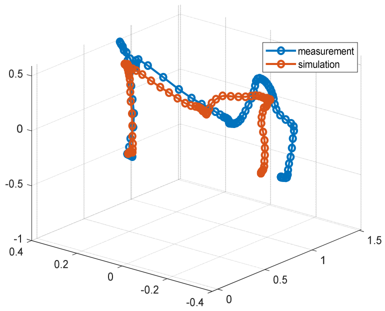


Fig. 3 Hand tracking result

Prediction Method of Shadowing Effect by Complex-shape Object in mm-Wave Band (A collaborative research with NTT) [42][47]

In the next-generation wireless communication system, millimeter-wave band radio (mmWave) is expected to realize the high network capacity. However, the mmWave also has the disadvantage that it can be shadowed by many objects in the environment. Thus, the prediction method of shadowing effect by object blocking is necessary for designing reliable wireless systems. Because the Geometry optics (GO) has poor accuracy in dealing with complex-shape objects and the full-wave analysis needs a large amount of the calculation resource at mmWave, we proposed to use the physical optics (PO) approach to predict the shadowing effect. In this research, we conducted the radio measurement at 66.5 GHz in an anechoic chamber to clarify the shadowing effect by the rectangular and human-shape metal plates. We evaluated the uniform theory of diffraction (UTD), knife-edge diffraction (KED), and PO simulation methods. Figures show the comparison results between the measurements and simulations by changing the position of the shadowing object. The result showed that the PO method could deal with complex-shape objects.

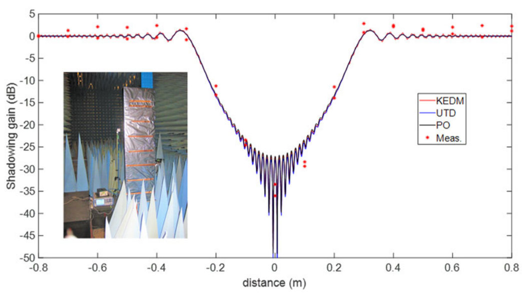


Fig. 1 Results of rectangular metal plane

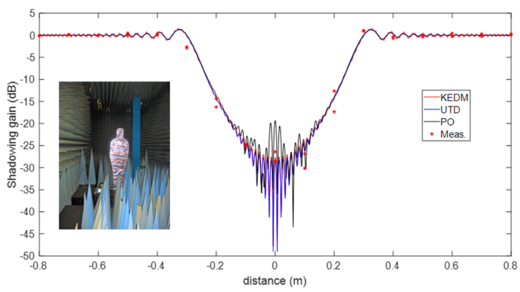


Fig. 2 Results of human-shape metal plane

Radio Wave Propagation for Underwater Wireless Sensor Networks (UWSNs) Deployment [18][22][45]

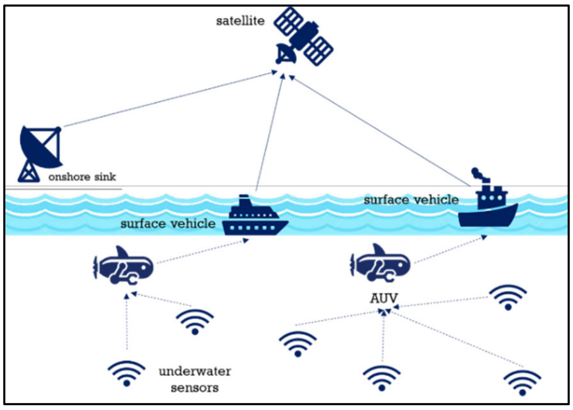


Fig. UWSN architecture.

Due to the complex nature of the underwater (UW) environment, several radio scientists and engineers have proposed techniques and technologies for UW communication applications and characterizations. To facilitate scientific explorations, improve survey efficiency, conserve marine life and habitat, and other UW applications, autonomous surface vehicle (ASV) and autonomous underwater vehicle (AUV) are being employed within the underwater wireless sensor network (UWSN) architecture, where a fixed UWSN comprising of two or more sensor nodes is integrated with a mobile UWSN (e.g. AUV). The mobile UWSN relays its collected data to the ASV via the transmitting and receiving antennas.

We study here the UW channel characteristics in detail to know their possible effects on different UWSN design considerations (frequency, link budget, required data rate, and transmitted power among others. We also aim to develop appropriate UW antennas for specific operating frequency. From the preliminary report, radio waves have been initially identified to severely attenuate due to the conductivity of water and have shown promising feasibility in the aquatic environment specifically for short or shallow distance scenario.

Theoretical Method Based Rain Attenuation Prediction for Millimeter-Wave Radio in Tropical Region [35][50]

Unprecedented growth in today's radio communication systems has compelled service providers to migrate to the mm-wave band so as to accommodate the ever-increasing data demands. However, the reliability of wireless systems at the mm-wave band tends to be severely degraded due to some atmospheric phenomena of which rain is the dominant factor, especially in tropical regions. Therefore, it is paramount to establish a model capable of predicting the behavior of such systems in the presence of rain.

In this study, by comparing the predicted rain attenuation results with measurement results in UTM, Malaysia, a new theoretical method based model using the knowledge of scattering properties of raindrops with different sizes and local raindrop-size distributions is found to produce better results than the widely-used empirical ITU-R model, particularly at high rain rate and high-frequency scenarios.

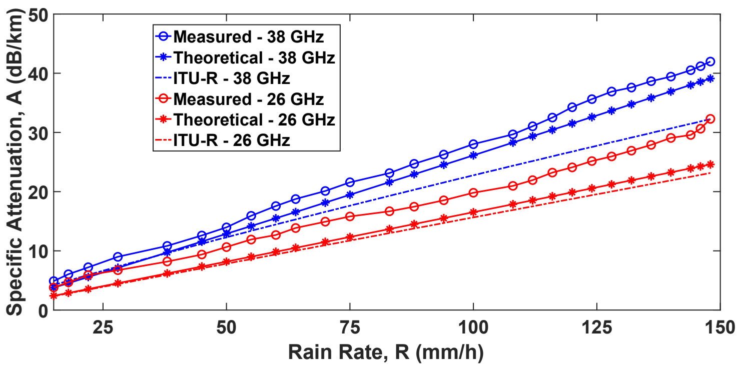


Fig. 1 Comparison of specific attenuation results

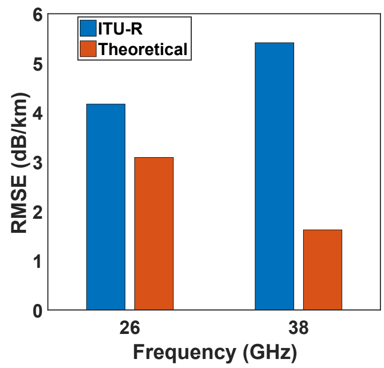


Fig. 2 RMSE of prediction results

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 Fraunhofer HHI in Germany as a Consultant. 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.

Recent Research Topics

- **mmWave Edge Cloud for 5G Cellular Networks**
- **mmWave Mesh Backhaul Networks and PoC Development**
- **mmWave Massive Relay MIMO**
- **4K Video Uncompressed Video Transmission from Drone Through mmWave**
- **mmWave V2X Communications and PoC Development**
- **Interference Cancelation for mmWave V2V Communications**
- **AR Glasses as 5G Terminals and Its Application in Smart Buildings**

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Sakaguchi-Tran Laboratory

Benefits of MEC 5G Cellular Networks

Why MEC is needed in 5G Cellular Networks?

In recent years, the total traffic in the cellular networks has rapidly grown with the blowout of smart services. To deal with this problem, 5G system adopts the millimeter-wave frequency band. Although the throughput at the access side has been greatly improved by 5G, the data traffic of each user grows due to the emergence of Cloud services in the mobile networks, such as video distribution services which are currently used via WiFi or wired networks. Apparently, the total Cloud traffic flow not only exerts pressure on the access side, but also on the backhaul side. Hence, the backhaul side would become a bottleneck because of the limited capacity. In order to eliminate the backhaul bottleneck, the authors focus on Multi-Access Edge Computing (MEC) deployed at the edge of the network in 5G cellular networks as shown in **Fig.1**. MEC has the capacity to provide a low end-to-end (E2E) latency, traffic load reduction on backhaul, high-speed cache downloading, etc. Owing to the prospect of MEC, various organizations have been established, such as Automotive Edge Computing Consortium (AECC) to further investigate and standardize the novel technology.

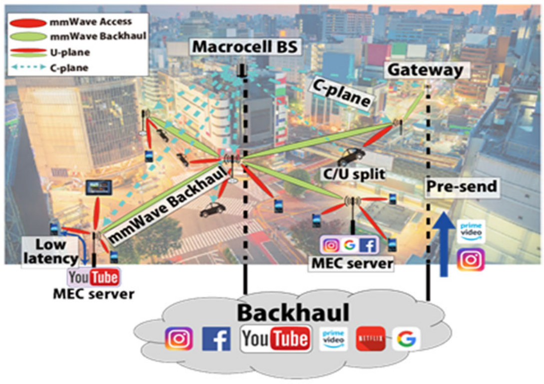
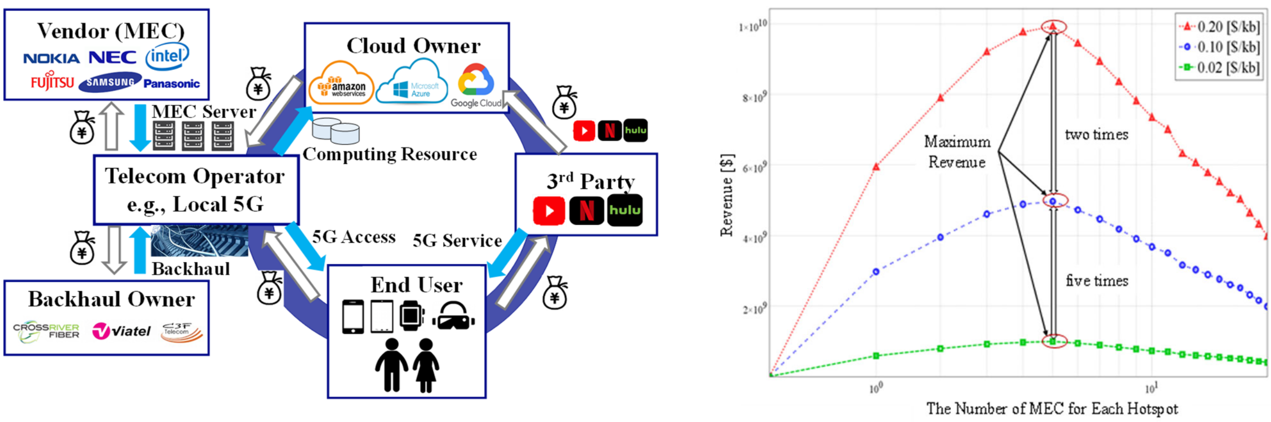


Fig. 1 Network architecture in MEC 5G

Design of MEC 5G Cellular Networks

Although testbeds or proof-of-concept (PoC) have been implemented worldwide, the feasibility and evaluation of the technology into real products and services is still unclear, especially from the operator's perspective. Besides, most of the state-of-the-art works in 5G and beyond only show the potential benefits of MEC in terms of solution for technical issues, but it is difficult for the operators to determine whether and how to install MEC in cellular networks, due to the uncertainty that whether a return on investment of MEC could be fed back. In our previous studies, we have proposed an ecosystem model for MEC 5G cellular networks as shown in **Fig.2(a)** and investigated how many MEC servers could maximize the revenue for telecom operator. In **Fig.2(b)**, with regard to revenue, it was found that the profit and loss tended to increase with the addition of MECs, and the number of MEC that could make the maximum profit depends on the MEC resource cost and application requirements.



(a) MEC ecosystem **(b) Focused on telecom operator revenue**

Fig. 2 MEC 5G ecosystem

Proof-of-Concept of Millimeter-wave Mesh Backhaul Networks

Introduction

Millimeter-wave overlay heterogeneous network (mmWave HetNet) is proposed to realize eMBB, however laying cost of backbone utilizing high-capacity optical fibers is very costly to support ultra-broadband accesses. Therefore, mmWave mesh backhaul networks (MMBN) and MEC are proposed to reduce mobile data traffic on backhaul networks in **Fig.3**. The architecture is enabled by wireless Software Defined Network (SDN) technology.

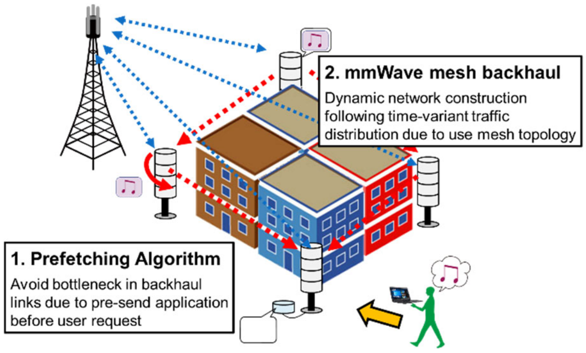


Fig. 3 Architecture of mmWave HetNet

1. Performance Evaluation of Prefetching Algorithm

In order to adapt to user movement, we design the network to pre-send (prefetch) application before the user requests it. **Fig.4** shows experiment environment, the MEC server follows the user movement when the system uses prefetching. The MEC server stays at node1 if the system without prefetching. **Fig.5** shows the result, which indicates the reduced download time due to avoiding the bottleneck in backhaul links.

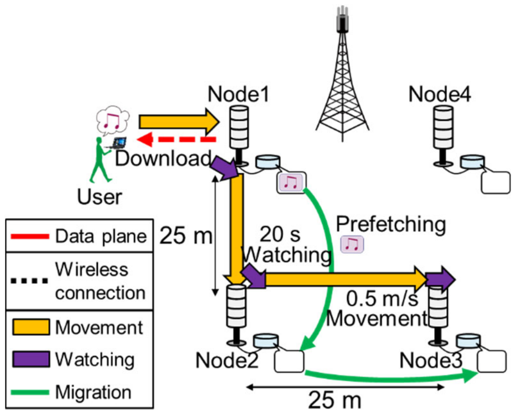


Fig. 4 Experiment environment

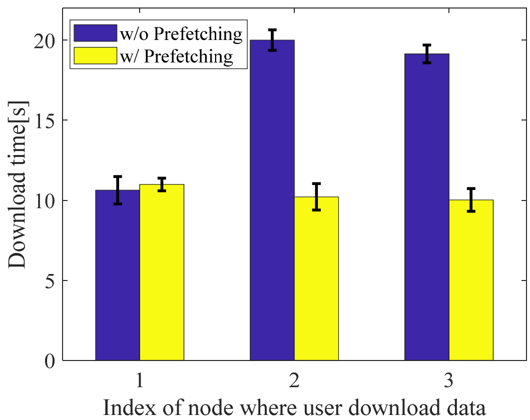


Fig. 5 Result of prefetching algorithm

2. Compact Design of MMBN and Experiment Results

We also design a compact type of mmWave mesh backhaul networks base station, which is shown in **Fig.6**. The volume of the backhaul antenna is 67% smaller than before. We did multi-hop relay throughput test with this base station, and the result is shown in **Fig. 7**.

Fig. 6 Compact design of mmWave base station

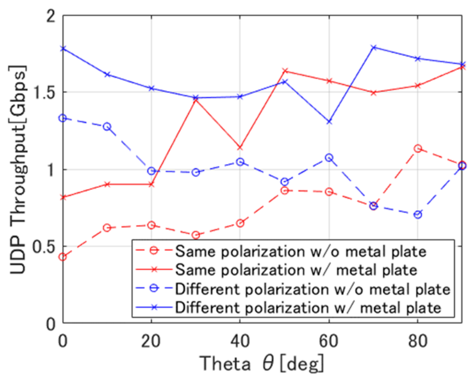


Fig. 7 Result of multi-hop relay throughput

Sakaguchi-Tran Laboratory

Cellular Networks by mmWave Massive Relay MIMO

Introduction

In the future, in 5G (fifth generation communication) and later communication technologies, with the advent of autonomous driving technology, it is expected that the way people spend time while traveling will change (ex. entertainment, work and meetings). Due to these changes,, users will demand a large data rate while traveling, such as watching high-definition video, working and videoconferencing in an automated vehicle.

There are mainly two ways to achieve this. The first is using 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 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 Relay MIMO System

Millimeter-wave Massive Relay MIMO can generate MIMO channel response artificially by using a large number of analog RSs. MmWave Massive Relay MIMO system not only supports MIMO transmission which was difficult to achieve in millimeter-wave, but also significantly improves the channel capacity. The analog RS node has two sides. One is the access side (UE side) connected to the UE and the other one is the backhaul side (BS side) connected to BS, and each of them can be beamformed using a multi-element antenna. we adopt AF type to reduce the delay of data transmission which is one of the main requirements of 5G.

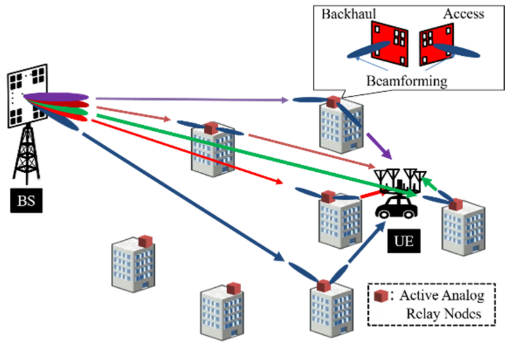


Fig. 8 Massive relay MIMO system

Simulation Analysis

Fig.9 shows the model which Massive Relay MIMO System is applied in an urban area. RS is placed above each building, the UE is moving in the direction of the arrow from (95,0) to (215,0) at 5m intervals in parallel with the x-axis. **Fig.10** shows the channel capacity. β is the amplification coefficient by each RS node. At points where more relay stations can be used, the channel capacity has improved significantly. As a result, it is confirmed that the channel capacity is greatly improved. Therefore, the effectiveness of Massive Relay MIMO is confirmed based on the result.

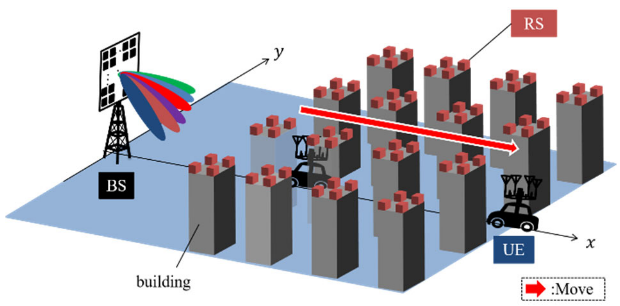


Fig. 9 Coverage characteristic

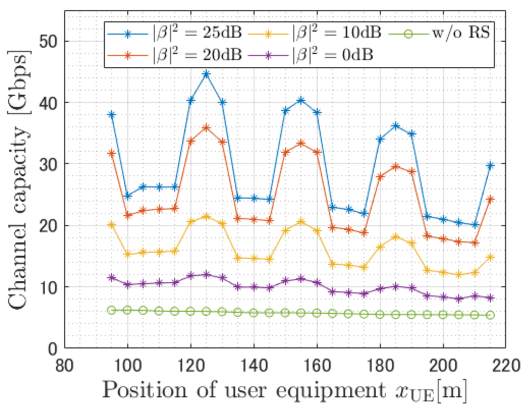


Fig. 10 Shannon capacity (w/ and w/o RS)

Proof-of-Concept of Uncompressed 4K Video Transmission from Drone through mmWave

Conventional Drone Surveillance System

In recent years, thanks to the miniaturization of electronic components and the development of high performance control techniques, drones have become one of the most promising technologies contributing to our daily life, and have been widely employed in varieties of citizen applications, such as surveillance, disaster monitoring. Conventionally, the surveillance systems only employ cameras with fixed locations because of the lacks of mobilities and the limitations of the energy supply. As a result, the surveillance systems always suffer the blind spots caused by the blockage or the inappropriate deployment of camera locations. To address the issue of the limited surveillance coverage, the active and seamless surveillance with no blind spots is expected to be realized by employing camera-equipped drones.

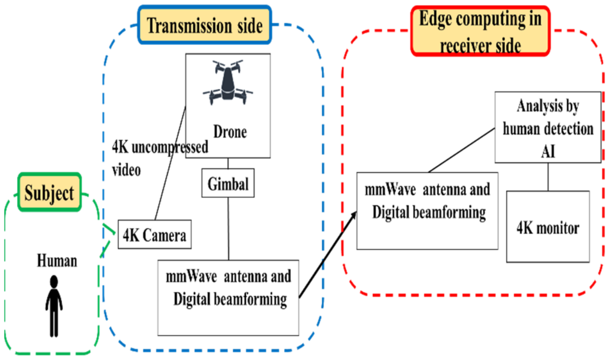
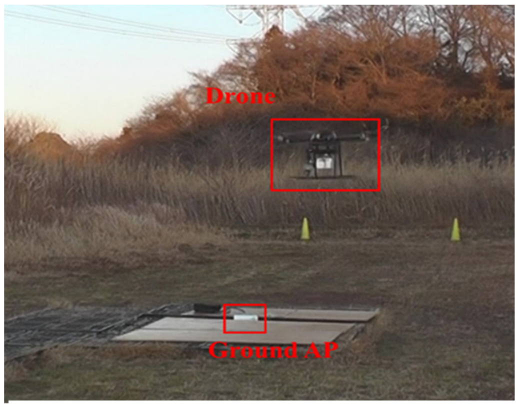


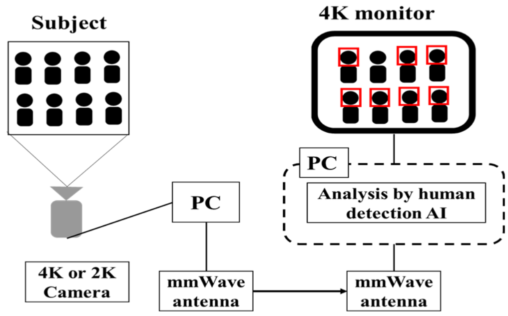
Fig. 11 System architecture

System Architecture and Experiment

Due to the large size of raw video footage, the original video needs to be encoded and then transmitted. However, the video quality is also a key factor affecting the performance of a video surveillance system. For example, in the face recognition application, which is one of the most important surveillance applications, the accuracy of face recognition decreases in proportion to the compression rate by applying compression processing to original images. Therefore, it can greatly improve the detection accuracy by employing the uncompressed ultra-high-resolution video. Then, we propose the uncompressed 4K video transmission system from Drone through mmWave. MmWave has the capacity to transmit the large size data like uncompressed 4K video. In addition, human detection AI using Edge computing at ground AP improves the object detection accuracy in drone surveillance system. **Fig.11** shows system architecture. In this research, uncompressed 4K video transmission and human detection experiment was conducted and we confirmed the effectiveness of this system architecture. **Fig.12(a)** shows the uncompressed 4K video transmission experiment composition. As a result, we succeeded in transmitting real-time 4K uncompressed video to a ground AP up to 100m. **Fig.12(b)** shows the human detection experiment composition and we compared number of recognized faces in uncompressed 2K with 4K. 2K recognized 45.5 out of 136 while 4K recognized 86.2 out of 136. It found that these result shows effectiveness of this system architecture.



(a) Uncompressed 4K transmission



(b) Human detection

Fig. 12 Experiment composition

Sakaguchi-Tran Laboratory

MmWave V2X Communications and Proof-of-Concept

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.

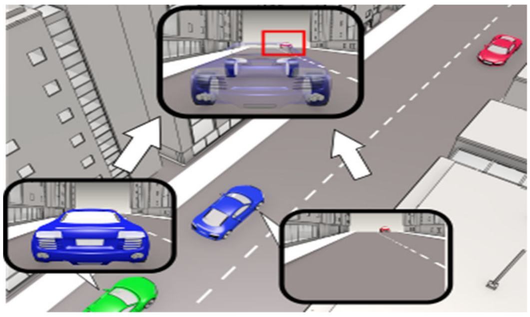


Fig. 13 Concept of cooperative perception

Software-defined mmWave Vehicular Network

The benefits of introducing SDN technologies into the traditional vehicular ad-hoc networks (VANETs) has been widely discussed, among which the most promising one is the capacity of dynamic resource management. Since mmWave V2X and backhaul become the future trends for vehicular networking, the integration with MEC (mobile edge computing) can be expected thus needing SDN management from a higher-level perspective to promote the content delivery. **Fig.14** shows a typical use case of dynamic HD map distribution in the software-defined mmWave vehicular network.

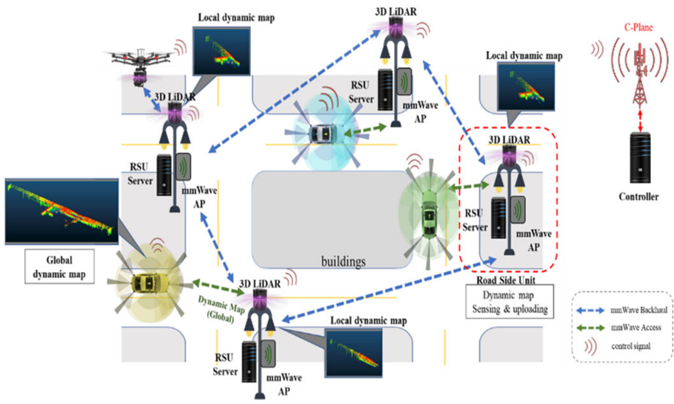


Fig. 14 System overview

Field Test

The hardware prototype of the software-defined mmWave vehicular network is implemented in the Yokohama Research Park (YRP) to demonstrate its performances. **Fig.15** shows the on-site deployment of network components including a pair of RSUs, an OBU and the critical SDN controller. A turning scenario with hidden risks is considered. Along the route, two-time cooperative perception will be realized when OBU approaches RSU1 and RSU2. The real-time position of OBU will be leveraged as context information to assist the radio resource management, i.e. SDN controller enables cooperative perception by controlling mmWave V2X access and dynamic backhaul routing for HD map distribution according to the context information of OBU.

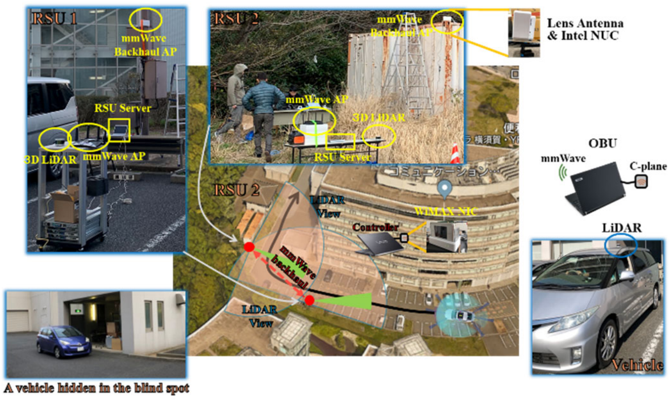


Fig. 15 Prototyping and deployment

Interference Cancelation for mmWave V2V Communications

In reality, there are often more than two vehicles in a single lane so that more than one mmWave V2V communication links are connected at the same time, so interference cancelation is an important issue to deal with. In the scenario of mmWave V2V, although the direct interference link can be completely blocked by vehicle bodies, the effect of reflected interference links is hard to overcome especially when antennas are located at the center of rear and front of the vehicle and the elevation and azimuth angles of antenna boresight are set to 0 degree. With this antenna configuration, the practical throughput of V2V communications usually appears lower than the required data rate during sensor information exchanging. Therefore, it leaves an open challenge for pioneering researchers to investigate more effective antenna configuration paradigms for mmWave V2V.

We propose a new method of ZigZag antenna configuration to control the interference, shown in **Fig.16**. The position of the antennas is changed owning to ZigZag deployment and the boresight of the antenna should be aligned with the variation of inter-vehicle distance.

Then an experiment is carried out to prove the effectiveness of ZigZag antenna configuration, shown in **Fig.17**. The real throughput can remain 1.2 Gbps with ZigZag antenna configuration.

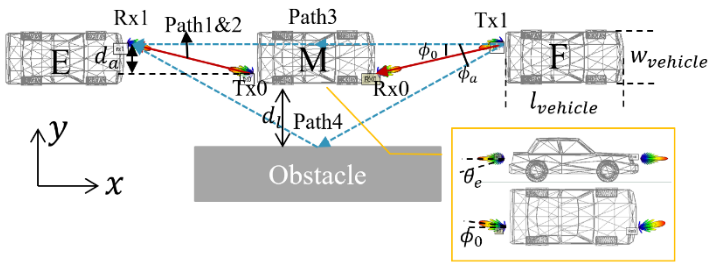


Fig. 26 ZigZag antenna configuration

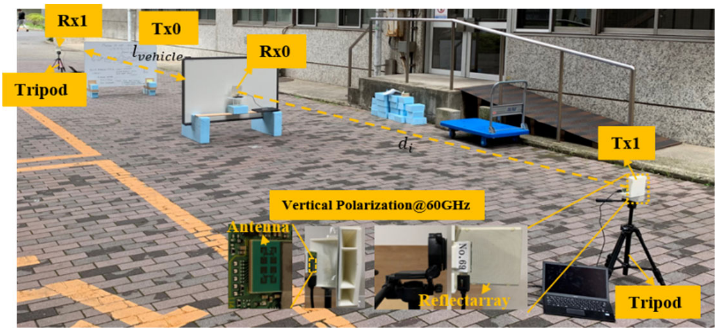


Fig. 17 Measurement scenario

AR Glass as 5G Terminal and its Application in Smart Buildings

Augmented reality (AR) superposing virtual objects or information onto real world has made great progress these years. However, there are still some limitations, such as narrow application, weak computing and short battery life. Fortunately, with support of 5G, these limiting factors will be expected to be overcome. Further, 5G promotes development of other technologies, such as smart building. Smart buildings provide users with access to information of the environment and a platform to manage various function units. These requirements can be satisfied by AR.

In the research, we utilize AR glasses in a practical smart building environment and set up an application platform integrating technologies which utilize AR glasses for visual interaction, AI for intelligent control, IoT for wireless sensor network and function units, and local network (5G in future) for wireless communication.

The application platform will coordinate modules to realize three basic tasks: environment data collection and command data processing, real-time interaction between users and platform, and wireless communication links setup. Additionally, users can easily detect surrounding information and control the platform by gestures or voice. A targeted use case can be a lighting control platform in a practical indoor office environment.

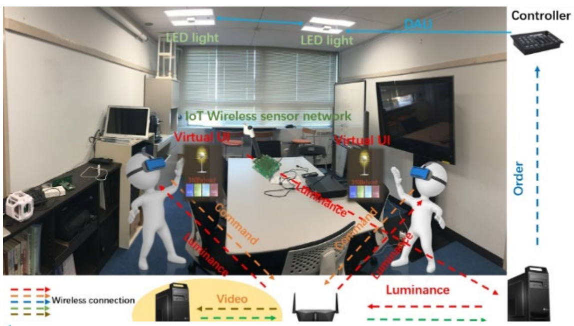


Fig. 38 Lighting control platform

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

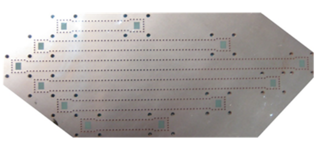
received the B.S., M.S. and D.E. degrees in electrical and electronic engineering from the Tokyo Institute of Technology, Tokyo, Japan, in 2008, 2011 and 2014, respectively. He was a Research Fellow of the Japan Society for the Promotion of Science (JSPS) in 2013. From 2014 to 2017, he worked at Mitsubishi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

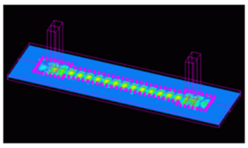
Dr. Tomura received the Best Student Award from Ericsson Japan in 2012 and the IEEE AP-S Tokyo Chapter Young Engineer Award in 2015 and Young Researcher Award from IEICE technical committee on antennas and propagation in 2018. He is a member of IEEE and IEICE.

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.

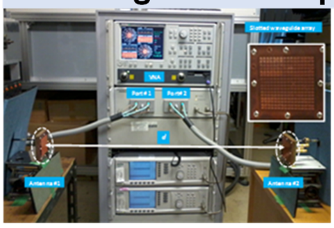
Post-wall waveguide

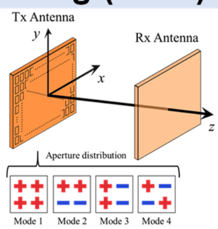




- Known as Substrate Integrated Waveguide (SIW)
- Published in the IEEE transaction in 1998 (Total citation: 308, Web of Science, 2017/6)
- Used as microwave and millimeter-wave band low-loss waveguide

Rectangular coordinate orthogonal multiplexing (ROM)

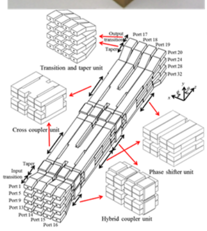




- Published in the IEEE transaction in 2017
- Equivalent to OAM transmission in the optical communication system, and apply to microwave and millimeter-wave applications

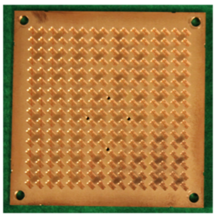
2-D beam-switching one-body Butler matrix

- 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)

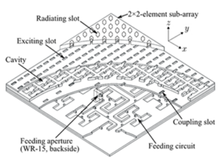


- $4^2 \times 4^2$-way one-body 2-D beam-switching waveguide Butler matrix
- Reduced its length and conduction losses by half.
- Reduced the number of components and volume.

Corporate-feed Slot Array Antenna with Plate-laminated Waveguide

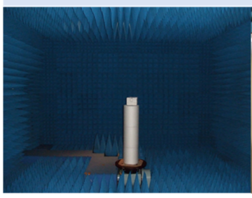


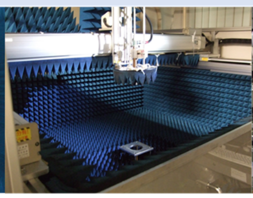
- Published in the IEEE transaction in 2011.
- After that, research is also started in Sweden, Singapore, China, etc.
- Designed in various frequency bands like 38-GHz band, 60-GHz band, and 120-GHz band, etc.



✓ 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

Analysis of Coupling Slots with a Reflection-canceling Wall for Parallel Plate Slot Array Antenna

A center-feed parallel plate slot array antenna is attractive for millimeter-wave application due to its high antenna efficiency, simple structure, and light weight. This research presents a center-feed waveguide feeder with inductive walls for a parallel-plate slot array antenna panel operates in millimeter-wave band. A design procedure of coupling slots is explained. The coupling slot array is analyzed by Galerkin's method of moments (MoM) which require less unknowns for the fast design. It is shown that computation time by using MoM is drastically reduced compared to commercial software HFSS. The design parameter relationship between HFSS and MoM models is found for compensating the inaccuracy caused by simplified assumptions in the MoM analysis.

The proposed antenna aims to operate in 9.50 GHz-9.80 GHz and its structure is illustrated in Fig.1. A WR90 waveguide feeder with coupling slots is located at the middle and beneath the parallel plates. A TE_{10}-mode from the antenna input travels in the x direction. After it arrives the τ junction, the power is equally divided and propagates in both the $+x$ and the $-x$ directions. The wave couples with the parallel plates through 15 inclined coupling slots on both sides of the τ junction. Inductive walls are used for reflection-canceling. The coupled waves then propagate in both the $+y$ and the $-y$ directions and radiate through radiating slot pairs. Two hard walls truncate the parallel plates for supporting TEM mode propagation.

The design of coupling slots for the feeder network aims to achieve minimum reflection in the waveguide and uniform field distribution in the parallel plate region. External mutual coupling effect among the coupling slots in the parallel plates are included by introducing periodic boundary conditions (PBC). A design procedure of the coupling slots is given. (1) Design the matching slot at edge by commercial software HFSS. A reflection below –15dB over the operation bandwidth is achieved. (2) Design regular coupling slot separately by the MoM unit model. The coupling is mainly controlled by the slot angle while the reflection is affected by the wall position. The reflection below –20dB is achieved for all the slots. The design parameter relationship between HFSS and MoM models is found for compensating the inaccuracy caused by simplified assumption in the MoM analysis.

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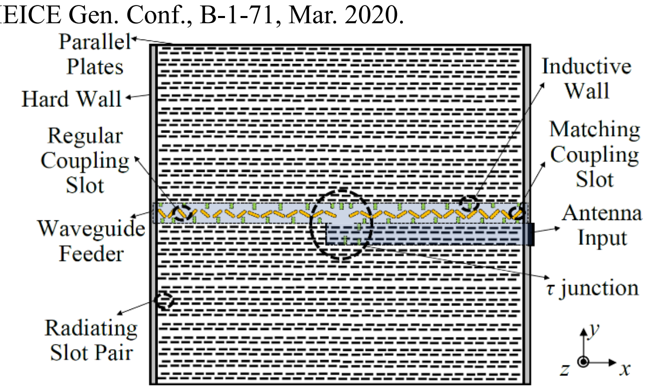

Fig. 1. Antenna Structure

Analysis of 2×2 Radiating Slots with Parallel-Plate Perpendicular-Corporate Feed Based on Method of Moments

The analysis of the perpendicular-corporate feed with 2×2 radiating slots is conducted by the method of moments (MoM). By applying the field equivalent field theorem on the slots in the model, the unknowns to be solved by this method are much fewer than those in simulation by the HFSS, thus faster analysis is achieved. As a result, the parameter optimization of the slot antenna array would be more time-efficient.

The model consists of a short-ended feed waveguide at the bottom and a square radiating part with 2×2 wide slots on the top, as shown in Fig.1. A longitudinal coupling slot is cut on the broad wall of the waveguide, with an offset from the midline and a distance of quadrant wavelength from the shorted wall. The radiating part is excited by it from the back center perpendicularly to the upper four slots. The slot spacing on the radiating plate is $0.86\lambda_0$ in the x and y directions. With no peripheral walls as in a cavity to hold the fields, a dielectric layer with permittivity of $\varepsilon_r = 2.17$ and an air layer are filled between the feeding and the radiating plates to excite standing waves in the region. The thickness of the plates in the model is also included in the analysis.

The good agreement of the calculated reflection coefficients with HFSS simulation verifies the accuracy of the method. Besides, the discrepancy in result using basis functions only from the longitudinal component of the magnetic currents verifies the necessity of including the transverse component for the wide radiating slots. It takes 12 seconds to get the reflection characteristics of the model in the 60 GHz-band by the proposed method, whereas much longer 29 minutes for HFSS. The superiority of applying the method will get clearer when more parallel plates are designed in the model.

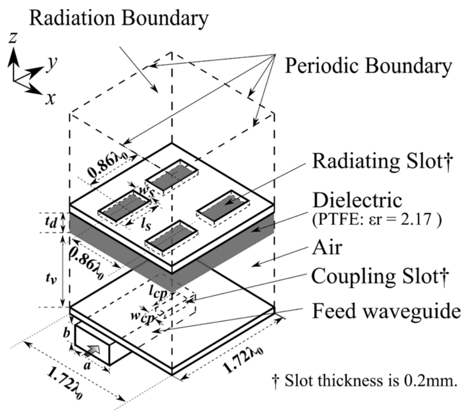

Fig. 1 Antenna structure

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Design of a Beam-Switching Circuit for Rectangular-coordinate Orthogonal 4-Multiplexing in the Non-far Region with Two-dimensional 180-degree Hybrid

Recently, a multiplexing transmission antenna using two-dimensional orthogonal polarity excitation in the rectangular coordinate system has been proposed, which is named as ROM (rectangular-coordinate orthogonal multiplexing) transmission. The authors propose a 4-mode ROM multiplexing antenna system by using a waveguide circuit. We design a self-compensating corrugated waveguide phase shifter for this system, then analyze a full circuit in the 64-68 GHz band.

Fig. 1 shows the proposed beam-switching circuit for the 4-mode ROM transmission. The system has two waveguide components: the 2-D hybrid (the waveguide 2-plane coupler) and the phase shifter. The former circuit is commonly used for an element for 2-D beam-switching Butler matrix. The output phase distributions of ROM modes are shown in Fig. 1. Port 1 excites Mode #1, Port 2 excites Mode #2 and so forth. The orthogonality among ROM modes decreases if phase errors of output beams get worse. To improve orthogonality, a phase shifter that achieves a constant phase shift in a broad bandwidth is required, therefore we propose a self-compensating corrugated waveguide phase shifter.

A self-compensating corrugated waveguide phase shifter is a combination of the broad-wall width control in the H-plane and the phase control by broad-wall corrugations in the E-plane. We design 0°, +90° and -90° self-compensating corrugated waveguide phase shifters.

The reflection coefficients of proposed phase shifters were below -36.7 dB at 66 GHz and below -28.5 dB in the 64-68 GHz band. The phase error was within 1.0° at 66 GHz and within 7.1° in the 64-68 GHz band.

We evaluated the reflection of a proposed beam-switching circuit by the sum of S11, S21, S31 and S41. The sum of reflection is -19.4 dB at 66 GHz, and below -14.6 dB in the 64-68 GHz band. The operating frequency band of the proposed circuit is 3.0 GHz while that of the conventional circuit is 2.0 GHz in the 64-68 GHz band. The phase error of the proposed circuit is within 15° while that of the conventional circuit is within 20° in the 64-68 GHz band.

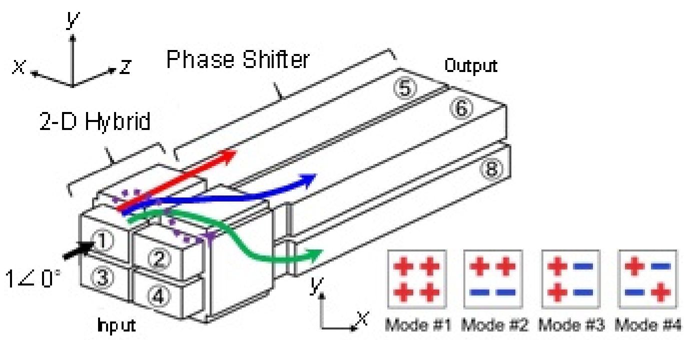

Fig. 1 Antenna structure

Referrence

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Control of Radiation Direction in an Aperture Array excited by a Waveguide 2-plane Hybrid Coupler

The waveguide 2-plane hybrid coupler has 2x2 ports at both sides of the coupled region as shown in Fig. 1. The ideal operation of this coupler is as follows. For an incidence from Port 1 as an example, Ports 1–4 have no outputs and Ports 5–8 have equal division in amplitude. Ports 6 and 7 have 90-deg. delay and Port 8 has 180-deg. delay in comparison with Port 5. The radiation from these four ports is tilted two-dimensionally. The four input ports switch the beam directions.

Each radiation aperture distance needs to be changed to control the beam direction. However, the positions of the ports cannot be changed because they affect coupling characteristics of the coupler. The authors propose to place a plate with taper waveguides and control the beam directions.

The beam radiation of the conventional waveguide 2-plane hybrid coupler is affected by diffracted waves at the edges of the coupler. The edges are rounded to suppress the diffractions. Taper waveguides are introduced to the output ports to suppress the reflections and change aperture distances with keeping the coupling condition of the hybrid.

The design frequency of this coupler and the plate is 66 GHz. The original coupler has rectangular waveguide ports of which sizes are 2.67x1.40 mm and the beam directions are ±20 deg. and ±29 deg. in the quasi H-plane and the quasi E-plane, respectively. The plate can change the beam direction in a range of ±18–38 deg. for the quasi H-plane control and of ±27–54 deg. for in the quasi E-plane control. Inductive irises are introduced to the tapered waveguides in the plate of which beam direction is ±54 deg in the quasi E-plane to match the impedance of the apertures and the wave impedance. For this plate, S41 is suppressed less than –20 dB in 65.1–66.4 GHz. However, S21 becomes more than –10 dB in frequencies higher than 64.3 GHz. This is caused by the mutual coupling between Port 5 and 7, or 6 and 8.

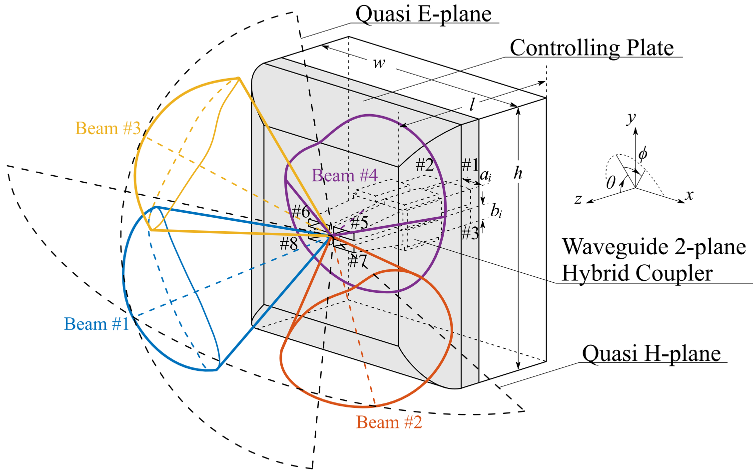

Fig. 1 Antenna structure

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Hirokawa Laboratory

Floquet Modal Analysis for Gap Waveguide

A gap waveguide has a single propagation Floquet mode in the stopband of electromagnetic bandgap (EBG) structure. The generalized scattering matrix (GSM) for the Floquet modes is suitable to understand the propagation of the gap waveguide. In this paper, we describe the modal analysis based on the Floquet modes for a groove gap waveguide (GGW) by using the hybrid analysis of mode-matching finite element method (MM/FEM). We firstly analyze the Floquet modes and the GSM based on the cross-sectional modes. The GSM based on the cross-sectional modes is converted to a GSM based on the Floquet modes.

Rectangular waveguide (RW) to Groove gap waveguide transition is shown in Fig. 1. The transition consists of discontinuity between RW and GGW. RW and GGW support TE10 mode and TE10-like mode in each waveguide, respectively. Gap waveguide doesn't need to perfect conduct between the top metal plate and the bottom metal plate with metal pins because gap waveguide has waffle-iron structures that don't allow the electromagnetic wave to propagate. In Fig.1 model, all materials are perfect electric conductor (PEC) that are lossless metal and sidewalls of the gap waveguide are also PEC to simplify the problem.

Firstly, GSM based on cross-sectional modes of the transition is analyzed by the mode-matching method. Secondly, we analyze Floquet modes of the gap waveguide by applying the Floquet theorem to the unit cell of the gap waveguide. Here, we can obtain generalized eigenvalue problem from GSM based on cross-sectional modes and Floquet theorem. Cross-sectional mode coefficients to express each Floquet mode can be obtained as eigenvectors of the eigenvalue problem. Finally, we convert mode basis of the GSM from cross-sectional mode to Floquet mode by using GSM based on cross-sectional mode and eigenvectors expressing Floquet modes. After converting mode basis, 5 propagation cross-sectional modes are reduced to single propagation Floquet mode. We have confirmed the amplitudes of reflection coefficients at both ports are identical and 2 types of transmission coefficients from one port to another port are identical. These relations are supported in the lossless reciprocal circuit whose ports have single propagation mode.

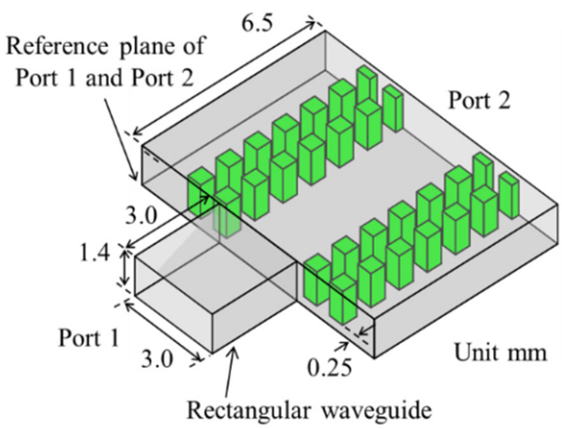

Fig. 1 Rectangular waveguide to groove gap waveguide transition

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Wireless Power Transmission by Radial Line Slot Antenna (RLSA)

Wireless power transmission has strong attention from industry for charging electric vehicles and drones [1]. We propose wireless power transmission system using two large array antennas placed in the near-field region. A radial line slot array antennas (RLSA) [2] [3] are used as Tx and Rx antenna. Because the Tx and Rx antennas are place in the near-field region, it is possible to transfer the power with high efficiency. In this paper, two different excitation phase distribution, uniform and rotation, are compared in terms of transmission distance and off-axis.

RLSA is composed of a feeding waveguide, a feeding slot, a radial waveguide and slot pairs as shown in Fig. 1 and 2. The slot pairs are arranged in coaxially with constant element spacing s_ρ and s_φ in both the ρ and φ direction. The radius of the first slot pairs is ρ_1 and the diameter of the RLSA is D. The feeding slot creates rotation or concentric mode in the radial waveguide according to the shape of the feeding slot. The slot pairs radiate circular polarization. When rotation mode is excited in the radial waveguide, all slot pairs are excited with uniform amplitude and phase and radiates into boresight direction. When concentric mode is excited, all slot pairs are excited with uniform amplitude and rotation phase exp($j\varphi$).

We proposed wireless power transmission system using RLSA. The transmission characteristics are studied for two different excitation phase distributions; uniform and rotation. All of the radiation elements was assumed as infinitesimal dipoles to calculate the transmission characteristics quickly without full wave simulation. The results showed that uniform phase excitation has longer coverage and better robustness of off-axis than rotation phase excitation.

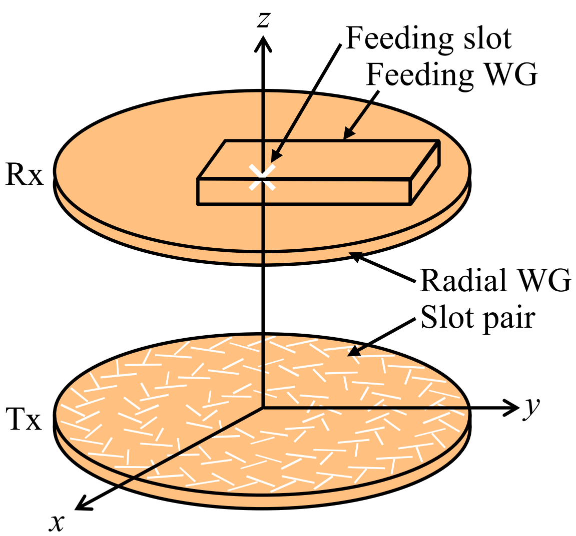

Fig. 1 Wireless power transmission system by RLSA

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Okada Laboratory

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

Professor Kenichi Okada

Professor Kenichi Okada received the B.E., M.E., and Ph.D. degrees in Communications and Computer Engineering from Kyoto University, Kyoto, Japan, in 1998, 2000, and 2003, respectively.
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.

Assistant Professor Atsushi Shirane

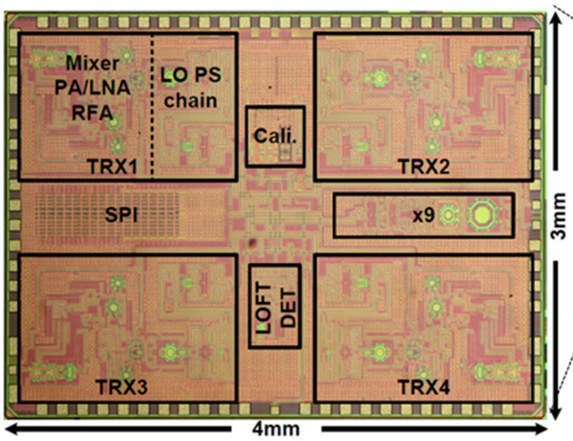
Assistant Professor Atsushi Shirane received the B.E. degree in electrical and electronic engineering and the M.E. and Ph.D. degrees in electronics and applied physics from the Tokyo Institute of Technology, Tokyo, Japan, in 2010, 2012, and 2015, respectively. From 2015 to 2017, he was with Toshiba Corporation, Kawasaki, Japan, where he developed 802.11ax Wireless LAN RF transceiver. From 2017 to 2018, he was with Nidec corporation, Kawasaki, Japan, where he researched on intelligent motor with wireless communication. He is currently an Assistant Professor in the Department of Electrical and Electronic Engineering, Tokyo Institute of Technology. His current research interests include RF CMOS transceiver for IoT, 5G, and satellite communication. He is a member of the IEEE Solid-State Circuits Society, and the Institute of Electronics, Information and Communication Engineers (IEICE).

Our Research Interests

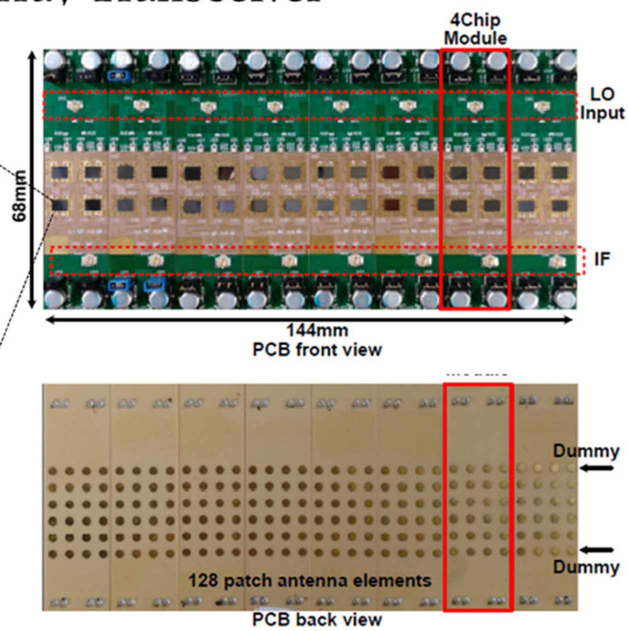
At Okada laboratory, we have been researching RF, analog and digital mixed signal integrated circuit design. Currently, we focus on the following research topics. In this report, we introduce the research highlight of this year about 1) 5G Transceiver, 2) Synthesizable PLL in 5nm CMOS.

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

5G Phased-array Transceiver

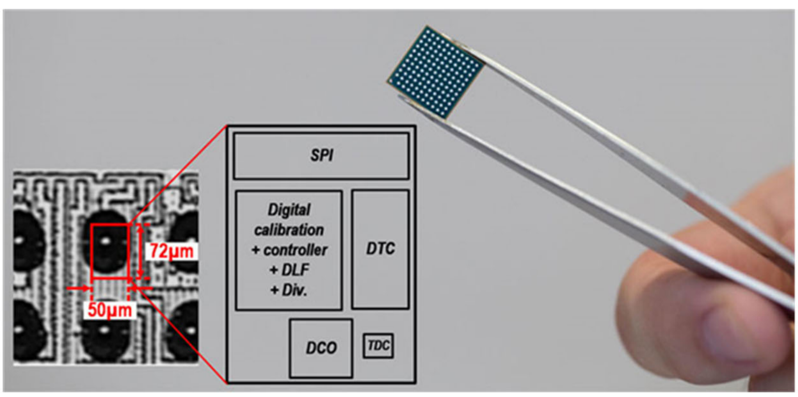


CMOS chip



Phased-array module

Synthesizable PLL in 5nm CMOS



Okada Laboratory

A 39GHz 64-Element Phased-Array CMOS Transceiver with Built-in Calibration for Large-Array 5G NR

Fifth-generation new radio (5G NR) wireless technologies will utilize millimeter-wave bands and beamforming for wider bandwidth, higher spatial efficiency and higher signal strength. To enhance the beamforming accuracy, especially for a large-scale antenna array used in base-station (BS), the antenna array excitations are required to minimize amplitude and phase mismatch. Recently, RF phase shifting and LO phase shifting phased-array transmitters and receivers are developed for 5G communication. The RF phase shifting transceiver suffers from high gain variation over the phase tuning range, which is usually worse than 1dB. The LO phase shifting transceiver shows high phase-tuning resolution, low gain variation and wideband characteristics. However, beamforming quality in the conventional study will suffer from phase drifting and gain expansion or suppression with supply and temperature changes. In this paper, a 39GHz 4-element LO phase shifting phased-array transceiver chip with built-in gain and phase calibration is presented. The on-chip calibration embedded in the proposed transceiver has an accuracy of 0.08-degree RMS phase error and 0.01-dB RMS gain error. The 39GHz phased-array transceiver supports 5G NR 400MHz 256QAM OFDMA in 1-m link over-the-air (OTA) measurement at band n260.

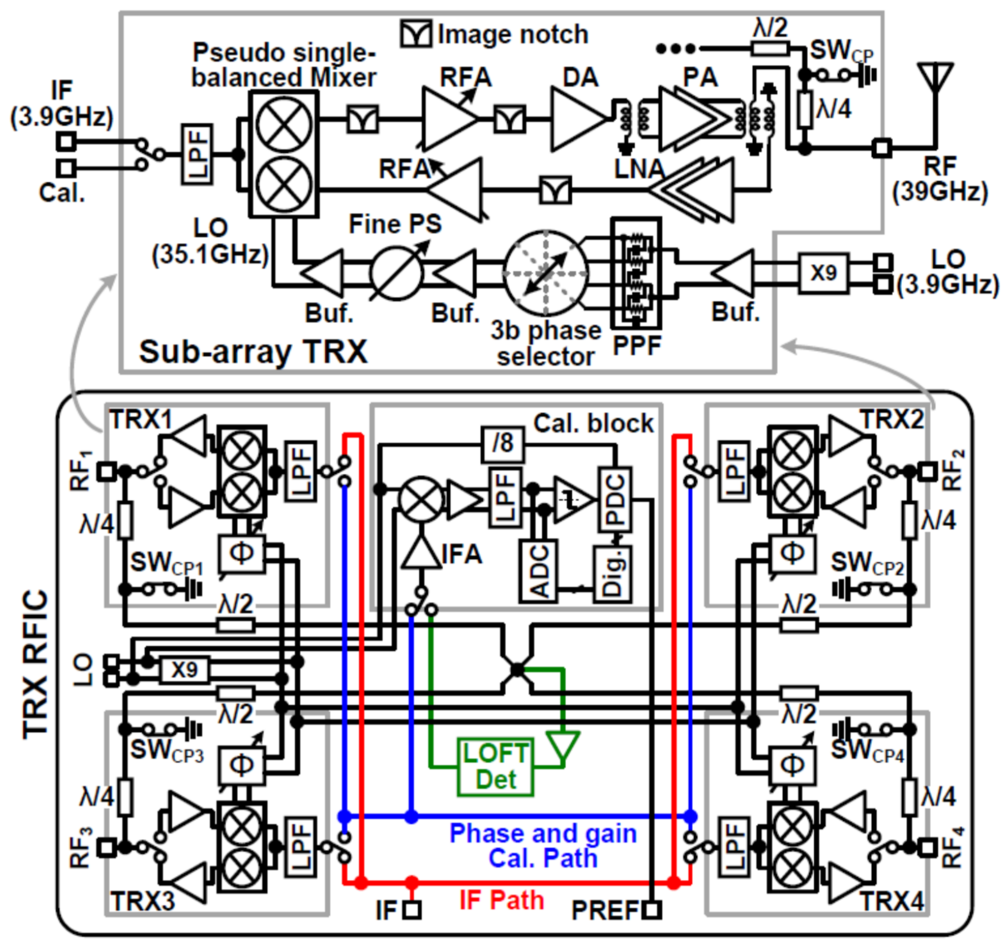


Fig. 1. Proposed 39GHz phased-array transceiver architecture.

Fig. 1 shows the proposed 39GHz phased-array transceiver architecture. The transceiver chip is composed of four sub-array transceivers, an LO frequency multiplier and a calibration block. A quarter-wave length transmission line based coupling network is used to switch between transceiver mode and calibration mode. The sub-array transceiver consists of a transmitter, a receiver and a LO phase shifter chain. The transmitter includes pseudo-single-balanced passive mixer, RF-amplifier (RFA), drive amplifier (DA) and two-stage differential power amplifier (PA). The receiver has three-stage LNA, RF-amplifier and pseudo-single-balanced passive mixer. Notch filters at image frequency are added in both TX and RX for image suppression. The LO-phase-shifting based architecture is chosen since it can achieve very fine beam steering resolution and gain-invariant phase tuning. The LO phase shifter chain is realized by employing a polyphase filter (PPF), a 3-bit phase selector and a fine phase shifter. For phase and gain quantization, the output of the receiver is connected for to the calibration block through a single-pole double-throw switch. The transmitting LO feed-through (LOFT) can also be detected by using a LOFT detector and the calibration block. The TX/RX switching, at the antenna side, is realized by the proposed transformer-based coupler. While at IF side the TX input and RX output are connected through the pseudo-single-balanced mixer for better linearity and phase-shifting isolation.

Fig. 2 shows the details of the phase shifter circuit schematic. The PPF quadrature output is connected to the 3-bit phase selector. The phase selector has eight steps with 45 degree phase shift of each step. Compared with the 90 degree quadrant phase selector, the proposed phase selector has a smaller phase step. Therefore, the fine phase shifter can be designed with a relaxed phase coverage, which improves the gain consistency over the varactor tuning range.

Fig. 3 shows the phase and gain calibration mechanism. A pair of TX and RX (not in the same sub-array) is used to calibrate the phase and gain characteristics. For example, RX3 is used to quantize TX1 phase gain values, and vice versa. The TX1 IF frequency fIF 0 and LO frequency f_{LO} has a small frequency offset (e.g. 120kHz). The RF signal containing TX1 phase gain information will be down-converted to a

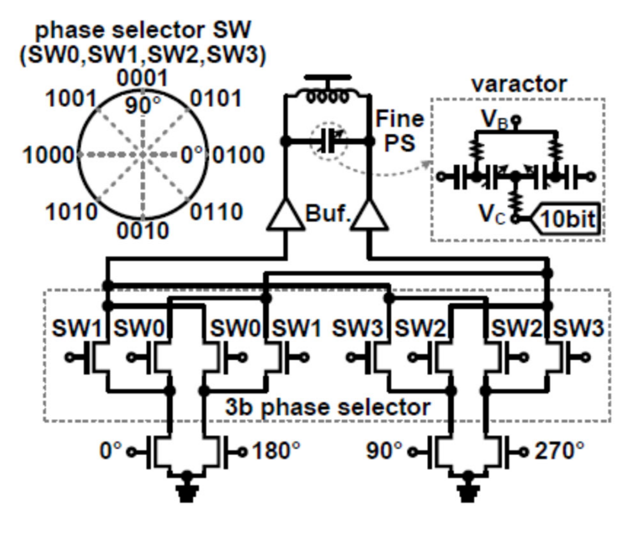


Fig. 2. Proposed phase shifter circuit schematic.

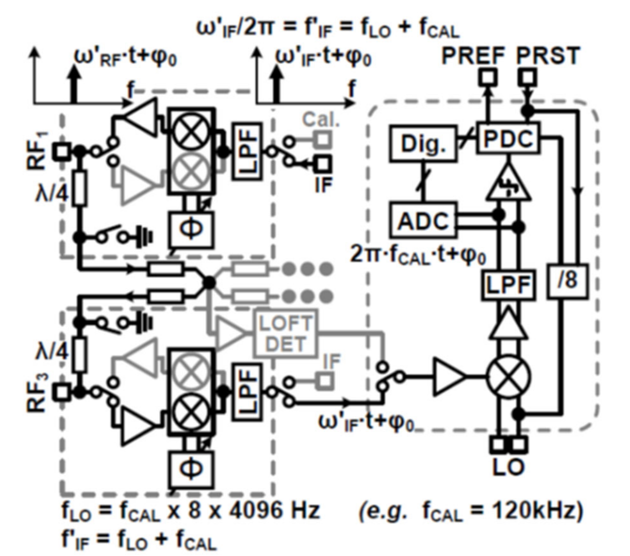


Fig. 3. Phase and gain calibration mechanism.

low frequency f_{CAL} in the calibration block. A 10-bit analog-to-digital converter (ADC) will quantize the gain value, and a 12-bit phase-to-digital converter (PDC) will quantize the phase value.

This study presents a 39GHz 64-element phased-array transceiver based on 4-element transceiver chipset with LO phase shifting architecture and built-in gain phase calibration. A phase-to-digital-convertor (PDC) and a high-resolution phase detection mechanism are proposed. The built-in calibration has a measured accuracy of 0.08-degree RMS phase error and 0.01-dB RMS gain error. The LO phase shifting based transceiver has a 0.04-dB maximum gain variation over the 360 degree full tuning range. The proposed pseudo-single-balanced mixer realizes -70 dBm LO-feedthrough (LOFT) cancellation and maximum 0.5 LO-to-LO isolation. The 8TX-8RX phased-array transceiver module 1-m OTA measurement supports 5G new radio (NR) 400MHz 256QAM OFDMA modulation with -30.0dB EVM. The 64-element transceiver has an EIRPMAX of 53dBm. The 4-element chip consumes a power of 1.5W in TX mode and 0.5W in RX mode. Fig.4 shows the comparison table of millimeter-wave phased-array transceivers for 5G and beyond. This paper demonstrates a 39GHz phased-array transceiver with built-in phase, gain and LOFT calibration, which can ease the deployment of the large array.

	This work	[1]	[2]	[3]	[4]	[5]
Frequency (GHz)	39 (n260)	28	60	28	29	28
Process	65nm CMOS	28nm CMOS LP	28/40nm CMOS	65nm CMOS	180nm SiGe	130nm SiGe
Architecture	LOPS	RFPS	RFPS	LOPS	RFPS	RFPS
PS resolution	3+10 bit / 0.05°	3 bit -	6bit / 6°	2+3+10 / 0.04°	6bit / 5.6°	1+5 bit / 5°
TX Psat/path (dBm)	15.5	14	6.5	18 (w/o SW)	12.5	16.4
Chip power dissipation (W)	1.5 / 4TX 0.5 / 4RX	0.36 / 4TX 0.17 / 4RX	8.4 / 144TX 6.6 / 144RX	1.2 / 4TX 0.6 / 4RX	0.8 / 4TX 0.5 / 4RX	4.6 / 16TX 3.3 / 16RX
Chip area (mm^2)	12	28	292 (full radio)	12	12	166
calibration	phase, gain, LOFT	N/A	N/A	N/A	gain, IQ	N/A
Max gain variation (dB)	0.04	-	1.5	0.03 (RMS)	0.8	1.5
RMS phase error (°)	0.08	-	-	0.28	6	1
TX LOFT (dBm)	< -70	-	-	-	-	-
Array size	64	24	288	8	32	128
$EIRP_{MAX}$ (dBm)	53	35 (8 ele.)	51	39.8	45	57
OTA TX to RX EVM (dB)	-30.2 400MHz 64QAM	-41 (TX only) 100MHz 64QAM	-24 (TX only) 1150MS/s 16QAM	-35 800MS/s 64QAM	-27 500MHz 64QAM	N/A
5G NR evaluated	Yes	Yes	N/A	No	N/A	N/A

Fig. 4. Performance comparison of mm-wave phased array transceivers for 5G and beyond.

A Fully-Synthesizable Fractional-N Injection-Locked PLL with Triangle/Sawtooth Spread-Spectrum Modulation Capability in 5 nm CMOS

The recent large-scale mixed-signal system-on-chips (SoCs) require more flexible clocking circuits to address the various challenges such as dynamic voltage and frequency scaling (DVFS) and spread spectrum clocking (SSC). Ring oscillator (RO)-based PLLs are highly demanded due to compact area, lower susceptibility to electromagnetic interference (EMI) and better amenability to process scaling. However, the ring oscillator phase noise is affected by supply and device noise. Therefore, the reduced supply and increased device noise in advanced processes degrade the ring oscillator noise performance. As a result, the RO-based PLLs in sub-20 nm CMOS processes have poor jitter-power FOM. Besides, the reduced supply voltage and increased variation make the analog circuit design more difficult in advanced processes. Moreover, the stringent design rules slow down the physical implementation and require more time and resources. Therefore, in this paper, a low-power high-performance IL-PLL is proposed as a clock generator. The whole PLL uses only digital standard cells, and its implementation is fully compatible with standard digital design flows. The noise of PLL and its building blocks, such as DCO and DTC, can be estimated and optimized with delay and power consumption information from the timing library. Novel system architecture and digital calibrations are adopted to ensure low-jitter and accurate frequency modulation.

The system diagram of the proposed PLL is shown in Fig. 5. the PLL adopted a triple-path architecture to realize the low jitter spread spectrum modulation. To suppress the high RO phase noise, a wide PLL

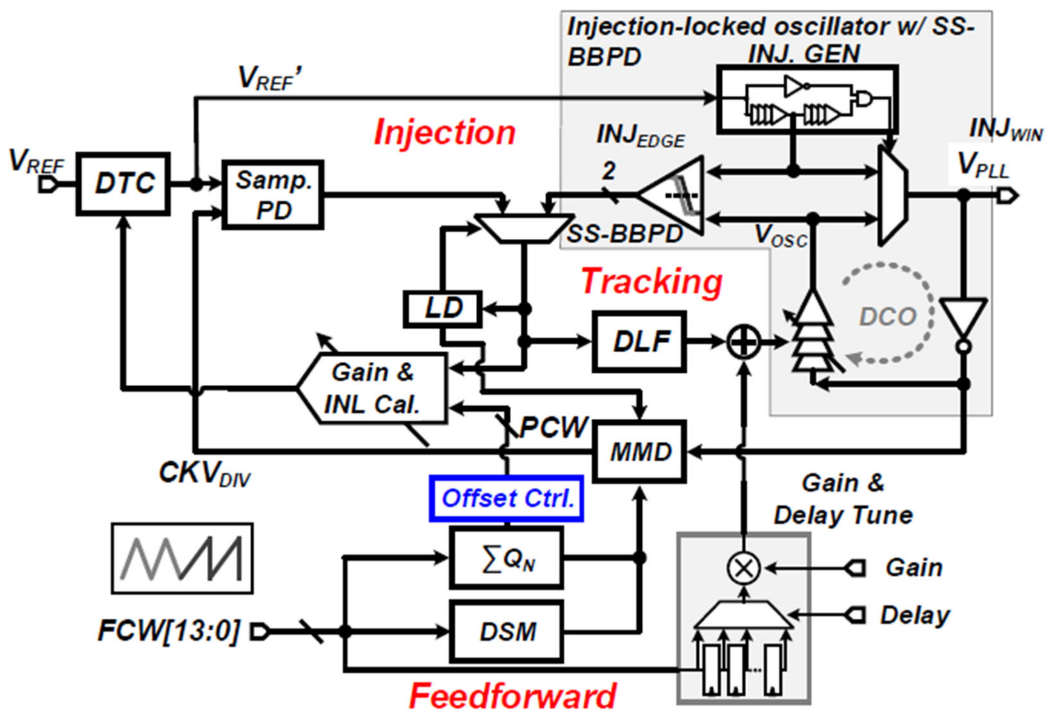


Fig. 5. System architecture of proposed fully-synthesizable PLL.

loop bandwidth is highly desired, which is realized with the injection path. Besides, to ensure low phase noise is achieved across PVT variations, a digital phase locking path is used to track the slow-varying phase error. A sampling/sub-sampling phase-lock loop is integrated. The lock detector (LD) logic is integrated to actively monitor the phase error, and adaptively switch between those two modes to ensure robust locking and low power consumption. One of the major challenges of SSC operation is the large frequency error during turn-around-point (TAP), which degrades the timing margin of the clocked circuits. This problem is especially pronounced for sawtooth modulation, in which the large frequency discontinuity cannot be tracked by the phase locking path. Therefore, a feedforward prediction path is integrated, which tunes the digitally-controlled oscillator (DCO) frequency simultaneously with the control code on the injection locking path. The digital frequency control word (FCW) is gain scaled and delay adjusted to match the injection path. The delay and gain settings are manually set in the current implementation. However, adaptive background control similar to the one in the previous work can be integrated into future implementation.

Fig. 6 shows the die micrograph and area breakdown of the proposed fully-synthesizable IL-PLL, The PLL is implemented in the TSMC 5nm FinFET CMOS process, and the core area is 0.0036mm2. The whole PLL is implemented as one layout with a single supply, with only digital standard cells. The total number of gates is 58,000. And techniques such as region constraints and relative placement are used to reduce the systemic mismatches from place and route (P&R). The performance of proposed PLL is summarized and compared with other recent published RO-based PLLs in sub-20 nm CMOS processes, as shown in Fig. 8. Compared to other PLLs, this design has the smallest area and the lowest fractional spur. Besides, and power-jitter FOM is the best in both integer-N and fractional-N modes.

A fully-synthesizable injection-locked phase-locked loop for digital clocking is proposed in this study. The PLL is implemented in a 5nm CMOS process, with only digital standard cells are used. With proposed triple-path operation and digital offset control for digital-to-time converter, low-jitter fractional-N frequency synthesis and highly-linear spread-spectrum clocking are realized with low power

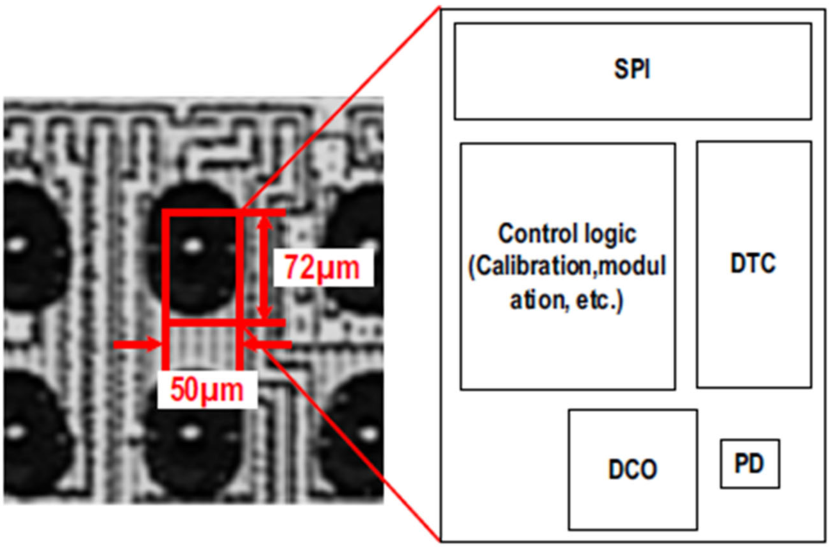


Fig. 6. Chip Micrograph in CMOS 5nm.

consumption. The PLL core area is 0.0036mm2. With 100MHz reference frequency, better than -234.7 dB figure of merit is achieved in the fractional-N mode, with -44.3dBc worst-case fractional spur. The proposed PLL has the smallest chip area, highest FOM, and lowest fractional spur among RO-based fractional-N PLLs in sub-20nm processes.

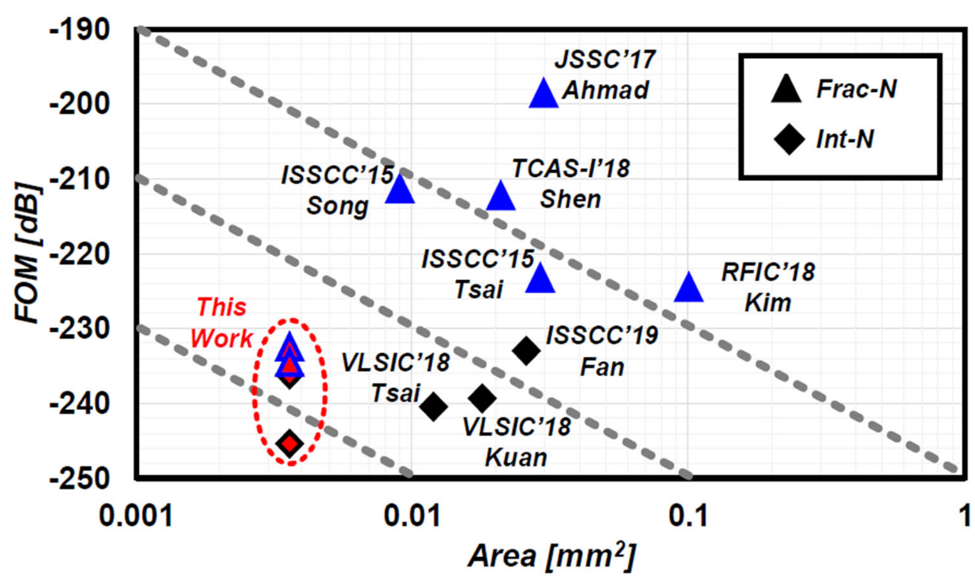


Fig. 7. Performance Comparison of Ring Oscillator Based PLLs in Sub-20nm CMOS Processes.

	This Work		TCAS-I'18 Shen [7]	RFIC'18 Kim [9]	JSSC'17 Ahmad [4]	ISSCC'15 Tsai [3]	ISSCC'15 Song [2]	ISSCC'19 Fan [8]	VLSIC'18 Kuan [5]	VLSIC'18 Tsai [6]
Frac-N/Int-N?	Frac-N							Int-N		
Synthesizable?	Yes		No	No	No	No	No	No	No	No
Arch.	Triple-path IL-PLL		DSM Analog PLL	MDLL + CPPLL	Counter PLL	All-digital PLL	Bang-bang DPLL	Analog CPPLL	Bang-bang DPLL	Hybrid PLL
Process	5 nm		14 nm	14 nm	16 nm	16 nm	14 nm	14 nm	7 nm	7 nm
Area [mm^2]	0.0036		0.021	0.1	0.03	0.029	0.009	0.026	0.018	0.012
fout[GHz]	1.0 (0.4-1.5)		4 (0.8-5)	7	3.25 (0.5-9.5)	3.0 (0.25-4)	2.0 (0.032-20)	3.2 (0.5-5)	4 (0.48-4)	4 (0.2-4)
Ref. [MHz]	40	100	100	52	60	50	-	100	30-250	200
Power [mW]	0.44*/0.62	0.52*/0.95	2.6	36.3	7.1	3.9	2.06	1.38*	6.3*	2.3*
Int. Jitter [ps]	2.34*/2.99	0.74*/1.90	15.1**	0.982	44	3.48	18.8	1.87*	0.43*	0.619*
FOM† [dB]	-236.2*/-232.6	-245.5*/-234.7	-212.3	-224.6	-198.6	-223.3	-211.4	-233*	-239.4*	-240.5*
Ref. Spur [dBc]	-37.1	-30.9	-51.5	-	-	-	-	-55.1	-61	-52.3
Frac. Spur [dBc]	-43.8	-44.3	-	-	-	-31.4	-	-	-	-
SSC capability	Yes		Yes	No	No	Yes	No	No	No	No
Modulation Profile	Triangle/Sawtooth		Triangle	-	-	Triangle	-	-	-	-
EMI reduction†† [dB]	18.7/20.4		19.5	-	-	19.2	-	-	-	-

* Int-N mode
** Estimated from T_j
† $\text{FOM} = 10 \cdot \log[(\sigma_t/1s)^2(P_{DC}/1mW)]$
†† Normalized to 1 GHz

Fig. 8. Performance Comparison of Ring Oscillator Based PLLs in Sub-20nm CMOS Processes.

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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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 control
- 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 at international conferences or accepted for publication in international journals.

Fukawa Laboratory

Iterative Receiver Employing Sparse Channel Estimation based on Kalman Filter for OFDM Communications [10], [15]

OFDM wireless channels are likely to be frequency selective fading, in which the absolute values of many propagation paths are negligible and can be called sparse channels. In addition, when the receiver moves rapidly, the channel varies fast due to the Doppler effect and thus, the accuracy of channel estimation deteriorates significantly. In order to alleviate its deterioration, the iterative channel estimation scheme with the tap selection and the least mean squares (LMS) algorithm exploiting log-likelihood ratios (LLRs) of the coded bits from the decoder has been studied. For further improving the channel estimation accuracy, we consider and enhance the fast iterative shrinkage-thresholding algorithm (FISTA) as an estimation algorithm for the sparse channel. In addition, we propose to apply the enhanced FISTA into both the initial channel estimation using several symbols long continuous pilots (CPs), and the soft decision directed channel estimation (SDCE) using replicas of transmitted signals.

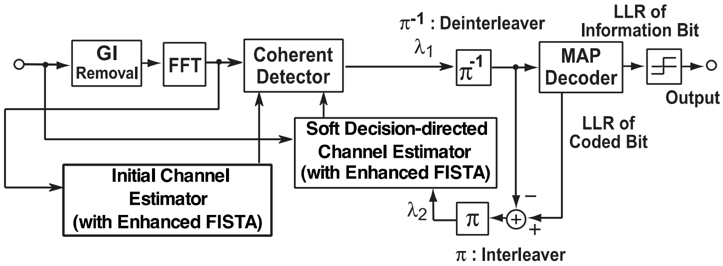


Fig. 1. A block diagram of the proposed OFDM receiver

Input: $\mathbf{C}(i), \mathbf{Y}(i), \mathbf{h}_e(i), \mu, \lambda$
Initialization: $\tilde{\mathbf{x}}_1 \leftarrow \mathbf{h}_e(i), t_1 \leftarrow 1, \kappa \leftarrow 1$
repeat
    $\boldsymbol{\alpha}(i) = \mathbf{Y}(i) - \mathbf{C}(i)\tilde{\mathbf{x}}_\kappa$
    $\mathbf{x}_\kappa \leftarrow \mathcal{T}_{\mu N_p{}^{-1}(i),\lambda}\left[\tilde{\mathbf{x}}_\kappa + \mu N_p{}^{-1}(i)\mathbf{R}^{-1}\mathbf{C}^{\mathrm{H}}(i)\boldsymbol{\alpha}(i)\right]$
    $t_{\kappa+1} \leftarrow \frac{1+\sqrt{1+4t_\kappa^2}}{2}$
    $\tilde{\mathbf{x}}_{\kappa+1} \leftarrow \mathbf{x}_\kappa + \left(\frac{t_\kappa - 1}{t_{\kappa+1}}\right)(\mathbf{x}_\kappa - \mathbf{x}_{\kappa\text{-}1})$
    $\kappa \leftarrow \kappa + 1$
until $\kappa = K$
Output: $\mathbf{h}_e(i+1) = \mathbf{\Phi}\mathbf{x}_K$

Algorithm 1. Kalman Filter (KF) based FISTA

Fig. 1 shows a block diagram of the OFDM receiver. The initial channel estimator (ICE) estimates a channel impulse response (IR) by using enhanced FISTA described later. The coherent detector then equalizes the received symbols using the transfer function of the channel as DFT of the estimated IR, and calculates the LLR of the coded bits. The LLR of the coded bit is deinterleaved and then fed into the maximum *a posteriori* probability (MAP) decoder. If any erroneous bits are detected from the output bit sequence, the receiver is switched to the iterative process. A more accurate IR is estimated by the soft decision directed channel estimator (SDCE) that estimates the channel by using the received signals and the replicas of the transmitted signals. Then, the receiver conducts coherent detection using the updated IR. The iterative process is repeated until no bit error is detected or the number of iterations reaches the preset maximum value.

Algorithm 1 shows Kalman-filter (KF) based FISTA. In this Algorithm, KF is formulated so that it can estimate both the channel IR and its first order differential with respect to time. Let μ and λ denote the learning step size and the ℓ_1-norm regularization parameter, respectively; and $Np(i)$ is the number of subcarriers in the i-th symbol. In addition, $\mathbf{Y}(i)$, $\mathbf{h}_\mathbf{e}(i)$ stand for the received signal vector and the estimated IR vector including its first order differential with respect to time. $\mathbf{C}(i)$, $\mathbf{R_0}^{-1}$, and $\mathbf{\Phi}$ are defined as

$$\mathbf{C}^T(i) = \left[\mathbf{C}_{n_1}^T(i), \mathbf{C}_{n_2}^T(i), \cdots, \mathbf{C}_{n_{N_p(i)}}^T(i)\right],\ \mathbf{C}_n^T(i) = S_n(i)\left[1, 0, e^{-\frac{j2\pi n}{N}}, 0, \cdots, e^{-\frac{j2\pi(D-1)}{N}}, 0\right],$$

$$\mathbf{R}_0^{-1} = \lambda_F^{-1}(1-\lambda_F)\begin{bmatrix}\lambda_F(1+\lambda_F) & \lambda_F(1-\lambda_F)\\ \lambda_F(1-\lambda_F) & (1-\lambda_F)^2\end{bmatrix},\ \mathbf{R}^{-1} = \mathrm{diag}[\mathbf{R}_0^{-1}, \mathbf{R}_0^{-1}, \cdots, \mathbf{R}_0^{-1}],$$

$$\mathbf{\Phi} = \mathrm{diag}[\mathbf{\Phi}_0, \mathbf{\Phi}_0, \cdots, \mathbf{\Phi}_0], \text{ and } \mathbf{\Phi}_0 = \begin{pmatrix}1 & 1\\ 0 & 1\end{pmatrix}.$$

Here, let λ_F, $D-1$, N denote the KF forgetting factor, the maximum delay time, and the number of FFT point, respectively. $S_n(i)$ is the modulation signal at the n-th subcarrier in the i-th symbol, and $\mathcal{T}_{\mu N_p^{-1}(i),\lambda}$ is the shrinkage function.

Computer simulations following the mobile reception in standard ARIB STD B-33, which adopts CP-OFDM, were conducted to verify the effectiveness of the proposed scheme. **Fig. 2** shows the average BER performance of ICE and SDCE with 4 iterations for both the proposed and conventional schemes. The proposed scheme achieves much better BER performance than the conventional scheme in ICE. Specifically, the proposed scheme acquires about 3 dB average E_b/N_0 gain at the average BER of 10^{-4}. **Fig. 3** shows the average BER performance of ICE and SDCE for both the proposed and conventional schemes under the condition that the normalized maximum Doppler frequency ranges from 0.1 to 0.2 and that average E_b/N_0 is 10 dB. It can be easily seen that the proposed scheme achieves better BER performance than the conventional scheme in such a range of $f_D T_s$.

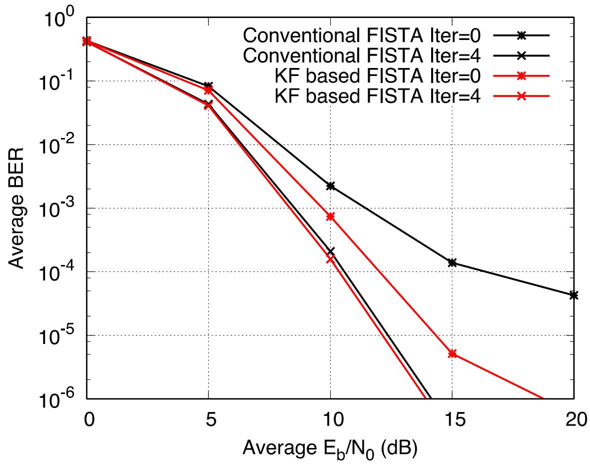


Fig. 2. Average BER Performance

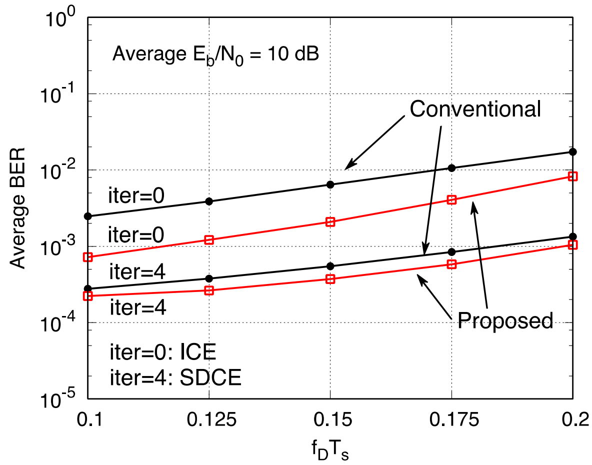


Fig. 3. Average BER performance vs. max. Doppler frequency

Parameter Estimation for Block Diagonalization based Hybrid Beamforming in Massive MIMO Communications [3]

Massive MIMO will be employed in the 5G. To implement the massive MIMO, hybrid beamforming (HB) is one of the most promising techniques, 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. Furthermore, HB can reduce a much larger amount of cost and power consumption than the full DB (FDB) configuration, which requires one baseband and RF circuit for each antenna element. We propose a scheme to estimate both phases for phase rotators in AB and a precoding matrix for DB so that HB can approximate the block diagonalization (BD), which can nullify interference from the undesired users and can form efficient transmit beams.

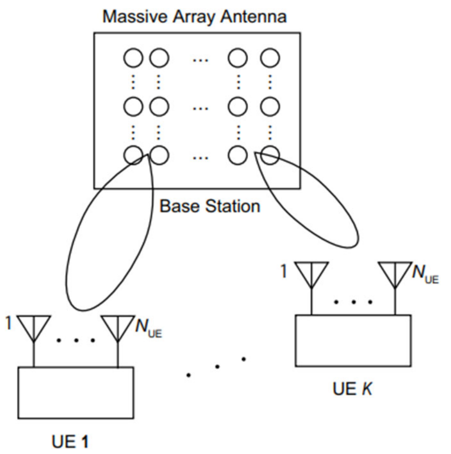


Fig. 4. Massive MU-MIMO system.

Let us consider a massive multi-user multiple-input and multiple-output (MU-MIMO) system shown in **Fig. 4**, where BS equipped with N_{RF} (> 100) antenna elements communicates with K user equipment (UEs). Each UE has N_{UE} antennas and shares the same frequency band at the same time. Since the TDD (Time Division Duplex) system is assumed, uplink (UL) uses the same frequency band as down link (DL). Owing to the channel reciprocity, BS can estimate the channel impulse response in DL and thus can control parameters of beamforming in DL. Although a time-invariant frequency selective fading channel model is assumed, the paper focuses on one subcarrier of orthogonal frequency division multiplexing (OFDM) and its channel can be regarded as flat fading. **Fig. 5** shows a block diagram of the massive MU-MIMO system. BS has M_{BS} RF chains and can provide up to a maximum of M_{BS} data streams. Each output of the RF chain is fed into N_{BS} phase shifters of which outputs are transmitted by the corresponding antenna elements.

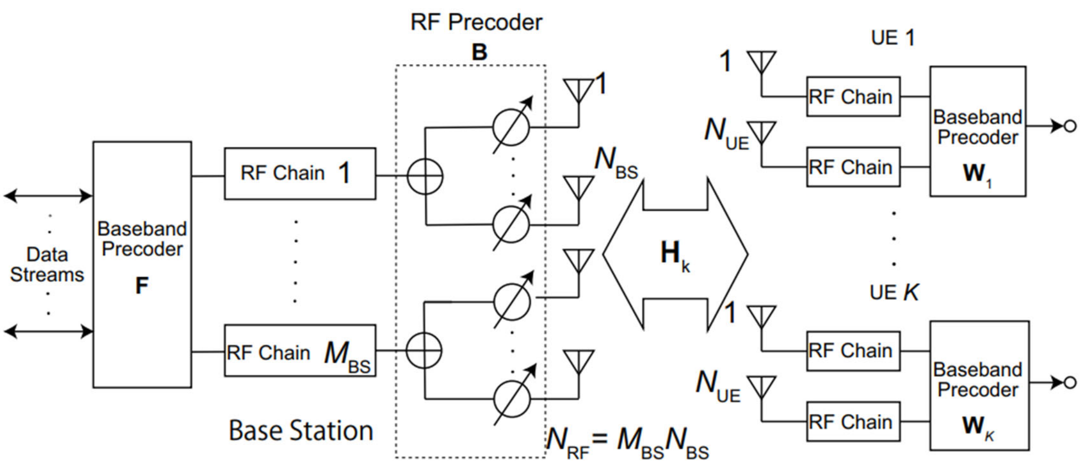


Fig. 5. Block diagram of the massive MU-MIMO system.

The proposed scheme consists of the following three steps: i) Firstly, it estimates the full channel matrix of each user in UL by considering that incident angle spread of propagation paths is limited. ii) Next, using the estimated full channel matrices, estimation of phases for phase rotators in AB alternates with that of a precoding matrix for DB, while such alternating estimation is repeated in DL. iii) Finally, the DB precoding matrix to approximate BD is obtained from the equivalent channel matrix, which is equal to the estimated FDB channel matrix multiplied by the AB precoding matrix.

The performances of the proposed scheme were evaluated by computer simulations in terms of the accuracy of channel estimation in UL and the average bit error rate (BER) in DL. **Fig. 6** shows NMSE (normalized mean square error) of the channel estimation in UL. When the average E_b/N_0 ranges from -30 dB to 5 dB, the normalized mean square error (NMSE) decreases with increasing angular spread of paths, because increasing angular spread can improve the diversity effect. When the angular spread is $5°$, however, NMSE exhibits an error floor with average E_b/N_0 being larger than 10 dB. This is because the angles of arrival (AoA) of the paths can be beyond the AoA set for the channel estimation. **Fig. 7** shows average DL BER of both FDB and HB when the angular spread is $5°$. It can be seen that the performance gap between FDB and HB is smaller than 5 dB and 7 dB, when the average BER is 10^{-2} and 10^{-3}, respectively. **Fig. 8** shows the average DL BER of each stream for HB with BD. The average BER is improved as the angular spread of paths increases. In addition, the gap between the 1st and 2nd streams is about 22 dB.

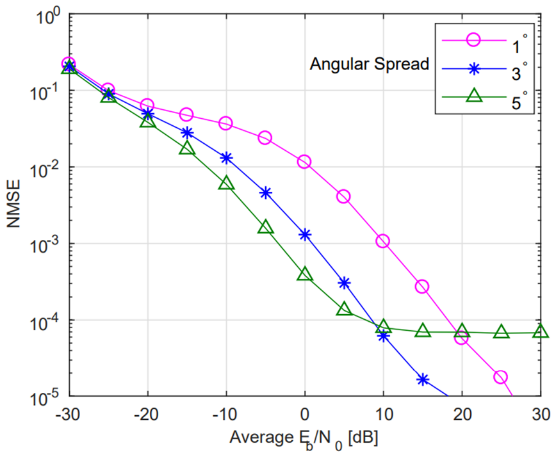


Fig. 6. NMSE performance of channel estimation in UL.

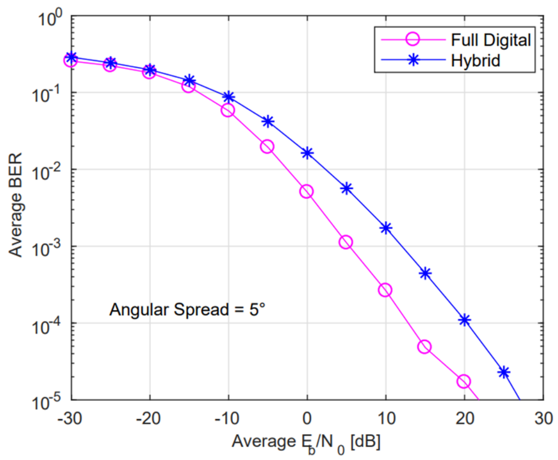


Fig. 7. Average DL BER of FDB and HB.

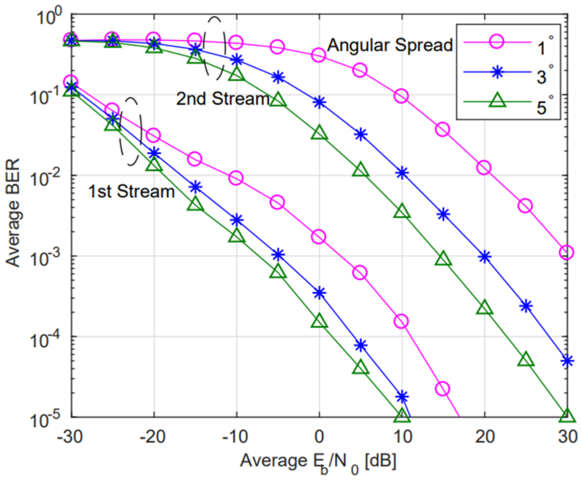


Fig. 8. Average DL BER of each stream of HB with BD..

Phase Rotated Non-Orthogonal Multiple Access (NOMA) [2]

Non-orthogonal multiple access (NOMA) is one of the most promising techniques to achieve high spectral efficiency for the next generation mobile communications (5G). In the NOMA downlink, a transmitter allocates different power levels to users and linearly combines user signals using the square roots of the power levels. On the receiver side, successive interference cancellation (SIC) cancels dominant interference in order to detect the desired signals. When a constellation point of the combined signal gets close to others, however, the bit error rate (BER) performance is degraded severely.

To overcome such degradation, a novel NOMA scheme with phase rotation (PR) for 2-user or 3-

user downlink transmission has been proposed. The proposed scheme rotates phases of the user signals and then linearly combines the resultant signals. To improve BER performance more than SIC, multiuser detection (MUD) is applied to signal detection of the user signal with the highest strength, whereas joint MUD and SIC is applied to that of the other user signals and can exploits the advantages of both MUD and SIC. In this report, 3-user transmission in the proposed NOMA scheme will be explained as an example. Methods for optimizing the angles of PR are proposed, so that the distance between the neighboring constellation points can be maximized.

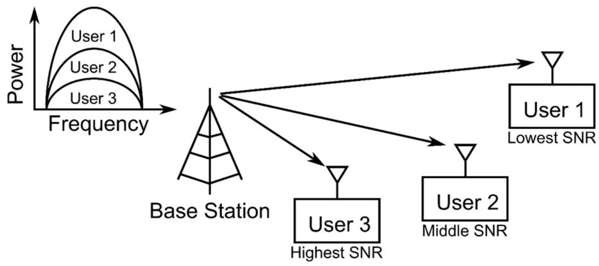
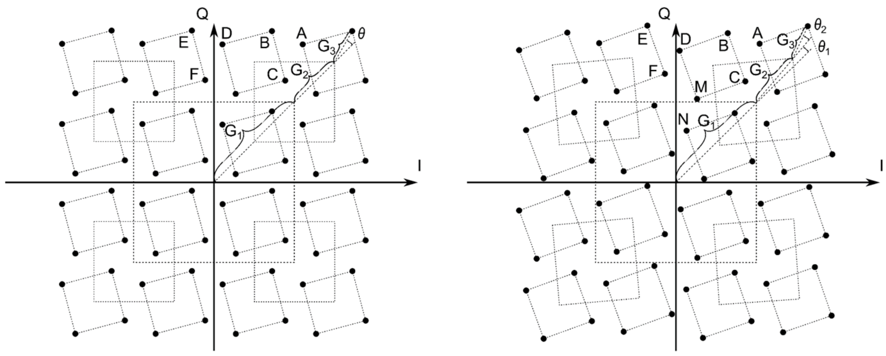


Fig. 9. A 3-user downlink NOMA system.

The considered 3-user downlink NOMA system is shown in **Fig. 9**. The base station (BS), which has one transmit (Tx) antenna, transmits signals to the three single-receive (Rx)-antenna users simultaneously over the same channel. BS assigns the highest, middle, and lowest Tx power levels to the lowest, middle, and highest SNR users, i.e., User 1, User 2, and User 3, respectively. Single carrier transmission with the non-Gray-mapped composite is assumed for simplicity. Two types of PR NOMA schemes are introduced, which are illustrated in **Fig. 10**, where the modulation schemes of all the users are QPSK. In Type 1, the Tx signal is defined as $x = G_1 x_1 + G_2 x_2 + G_3 \exp(j\theta)\, x_3$, where x_i, $i = 1, 2, 3$, is the complex modulation symbol of the i-th user, and G_i is the amplitude gain for x_i, and $P_i = G_i^2$ is the Tx power assigned to User i. In Type 2, the Tx signal is given by $x = G_1 x_1 + \exp(j\theta_1)\,[G_2 x_2 + G_3 \exp(j\theta_2)\, x_3] = G_1 x_1 + G_2 \exp(j\theta_1)\, x_2 + G_3 \exp(j\theta_2')\, x_3$. The ranges of θ and θ_2 are both $[0, \pi/4]$, and that of θ_1 is $[-\pi/4, \pi/4]$. The optimized phase can increase the minimum distance between the superposed constellation points, which can improve the BER performance of NOMA drastically, even when: 1) P_1 is close to $P_2 + P_3$, and/or 2) P_2 is close to P_3. Note that the information on the rotated phases can be fed forward to the users together with the allocated power levels, or it can be derived from the fed forward allocated power levels.



(a) Type 1 (b) Type 2

Fig. 10. Superposed constellation points.

The receiver employing the standard MUD for the users in the 3-user NOMA case is shown in **Fig. 11**. The MUD calculates the log likelihood function of the users as

$$\alpha_i(s) = \frac{|y_i - h_i s|^2}{\sigma_i^2},$$

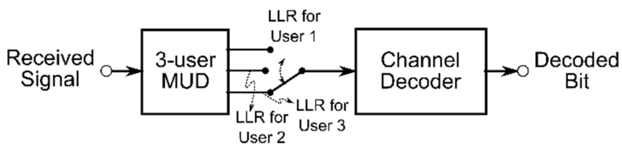


Fig. 11. A block diagram of a receiver with the standard MUD for the users.

where y_i, h_i and σ_i^2 are respectively the Rx signal, the channel impulse response and the Rx noise power of the i-th user. $s \in \mathcal{S}(\theta)$, and $\mathcal{S}(\theta)$ is the set of candidates for the Tx signal x, which is defined previously, and is a function of θ, or $\{\theta_1, \theta_2\}$. Using the log likelihood function, the log-likelihood ratio (LLR) of a coded bit $b_a^{(k)}$ for the i-th user's receiver is obtained as

$$\lambda_i\left(b_a^{(k)}\right) = \min_{s\left(b_a^{(k)}=0\right)} \alpha_i(s) - \min_{s\left(b_a^{(k)}=1\right)} \alpha_i(s),$$

where $b_a^{(k)}$ (k = 1, 2, 3) is the a-th bit corresponding to x_k in the Tx signal, where i and k are indexes to clarify the receiver of the i-th user and the bit of the k-th user, respectively. The LLR for each user is passed into the corresponding channel decoder. Finally, the information bit sequences for the users are decoded.

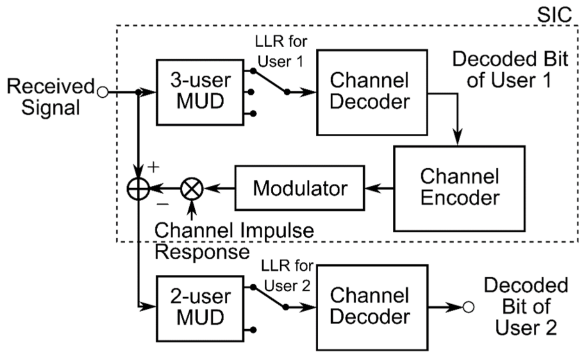
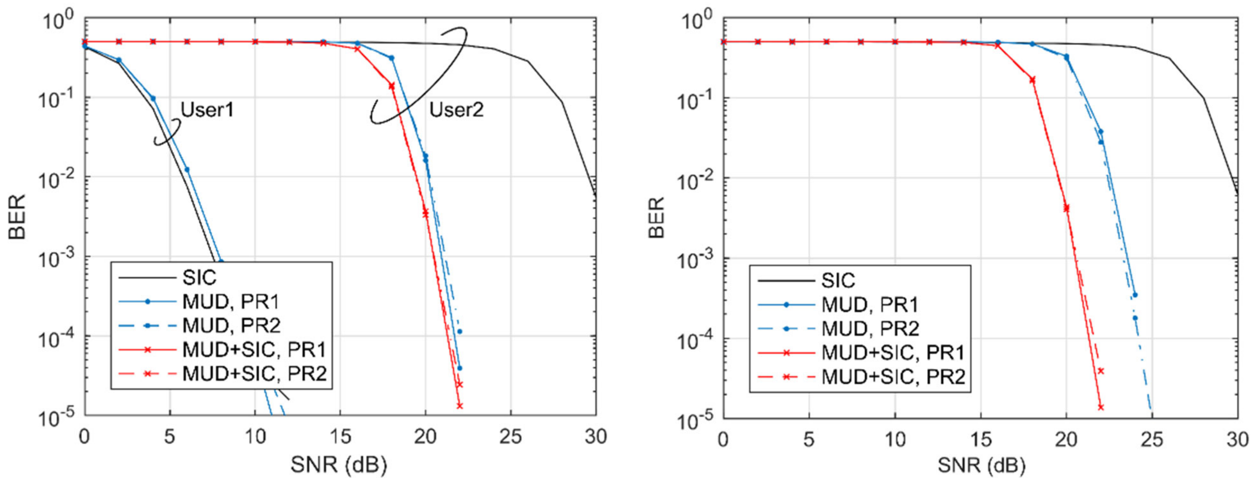


Fig. 12. A block diagram of joint MUD and SIC for User 2.

When the minimum distance between the superposed constellation points is maximized but still very short, the BER performance of even the receiver shown in **Fig. 11** degrades severely. To alleviate this degradation, we propose joint MUD and SIC shown in **Fig. 12**. Since the MUD does not regard the signal to Users 2 and 3 as interference, the MUD can improve the BER performance of User 1 compared to the single user detection (SUD). SIC can produce more accurate replica signals of User 1 by exploiting the decoded bits of User 1. Subtracting such replica signals from the received signals can increase the minimum distance between the complex modulation symbols of User 2, which can improve the BER performance of User 2.

In **Fig. 13**, which is an example of $P_1 : P_2 : P_3 = 0.75 : 0.14 : 0.11$, It can be seen that MUD is a little inferior to SIC in BER of User 1. This is because some constellation points of the combined signal can degrade reliability of the User 1 signal detection by MUD more than that by SIC. It is also seen that employing joint MUD and SIC for the proposed NOMA systems can achieve the best BER performance of Users 2 and 3.



(a) User 1 and User 2 (b) User 3

Fig. 13. BER performance of an example case.

Nishikata Laboratory

Home page: http://www.ns.cradle.titech.ac.jp

Associate Professor Atsuhiro Nishikata

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

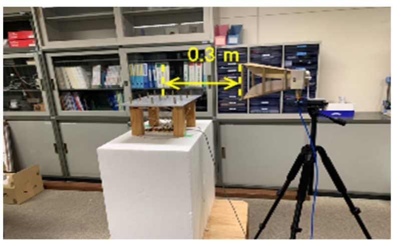
Recent Research Topics

- **Communication Experiment at 2.4 GHz by ASK-modulated Retroreflector**
- **Detection Experiment at 2.4 GHz by M-sequence-modulated Retroreflector**
- **Impulsive Magnetic Source Localization by Two Loop Antennas and a Turntable**
- **Analysis for Induced Noise on Communication Line by MAGLEV Train**
- **Common Mode Noise Suppressor by Ferrite Cores and Negative Impedance Converter**

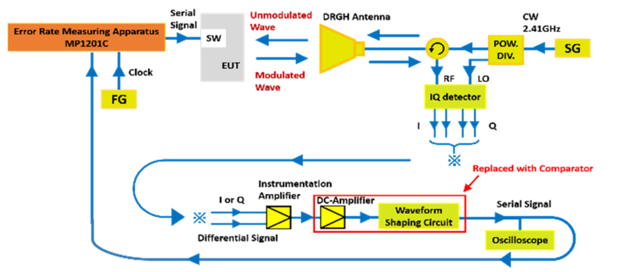
A Communication Experiment at 2.4 GHz Band by Using ASK-Modulated Retroreflector (A collaborative research with NTT)

In recent years, radio resources such as allocated frequency, polarization, space, and time have been tightened due to the rapid increase of wireless stations such as mobile phones as well as the speed-up of wireless communication. In this study, the concept of retroreflective communication is proposed to solve the problem, and a communication experiment using a prototype Van Atta array was performed and its characteristics were evaluated.

First, BER measurements was performed to evaluate the serial communication performance of the

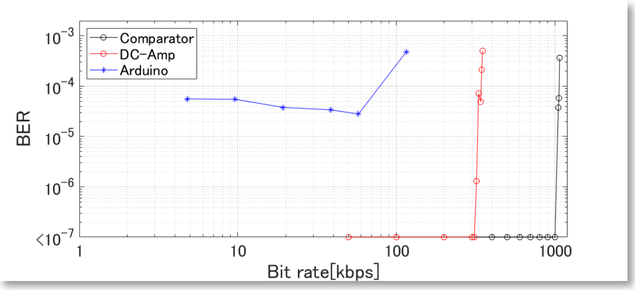


Experiment

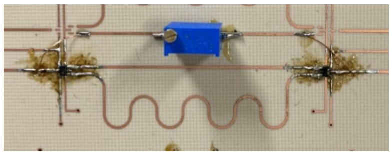


Experiment System

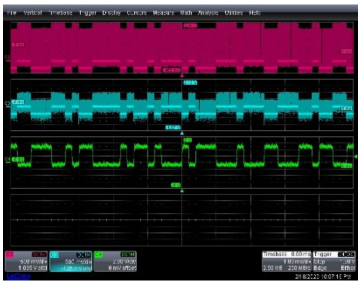
retroreflector. In the experiment, the 2.41 GHz unmodulated wave was radiated to the retroreflector, and the ASK-modulated retroreflected wave was received by a DRGH antenna homodyne-detected by the I/Q demodulator, converted back to a serial signal. Measurements were carried out using three kinds of setups; using Arduino microcomputers at Tx and Rx sides, using BER measuring instrument and DC amplifier, and using high-speed comparator instead of DC amplifiers in the latter setup. The performance was improved up to 1060 kbps within practical BER($\leq 2\times10^{-4}$).



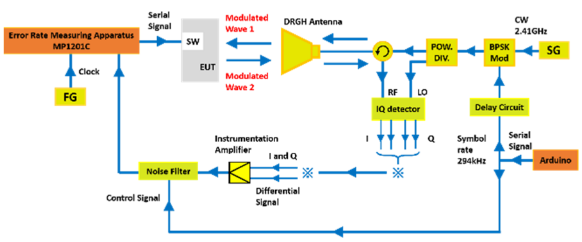
Second, the experiment for realizing full-duplex communication was performed using a retroreflector. The 2.41GHz BPSK-modulated wave was used as carrier, and further modulation was made by the retroreflector, then the influence of the forward modulation was attempted to remove from the reflected wave. The influence of the forward modulation remained due to the imperfection of the BPSK modulator, then it was eliminated by introducing a canceller circuit or improving the BPSK modulator itself. Next, spike noise remained after the removal of the forward modulation, then it was successfully removed by use of a median filter. On the other hand, spike noise elimination circuit using a sample / hold circuit, a voltage follower and a DC amplifier was prototyped to remove noise in real time and attempted noise elimination. As a result, it succeeded in suppressing the voltage of the spike noise to about zero (Green wave on the left figure). Finaly, BER measurements was performed to evaluate the full-duplex communication performance of the retroreflector. The 2.41 GHz unmodulated wave was BPSK-modulated and distributed to two by turning on / off the electronic switch built into the BPSK modulator by a serial signal from the Arduino microcomputer. One was radiated as a carrier wave to the Van Atta array retroreflector, and the other was used for the LO signal of the I/Q detector. The reflected wave from the retroreflector became a double modulated wave that was further ASK modulated. This was received by a DRGH antenna, I/Q detected, and only the modulated signal on the return path was successfully extracted through a noise removal circuit. At this time, BER measurement using Q signal was performed, and it was confirmed that up to 27 kbps within practical BER($\leq 2\times10^{-4}$).



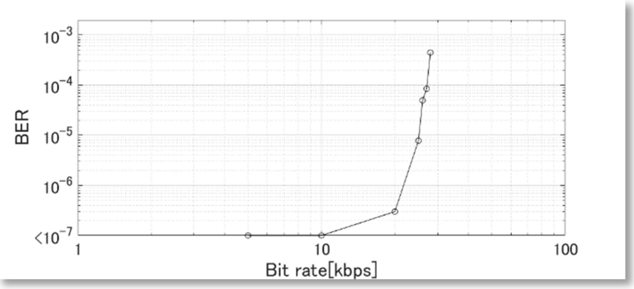
BPSK modulator



Q-channel **waveform**



Experiment System



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.

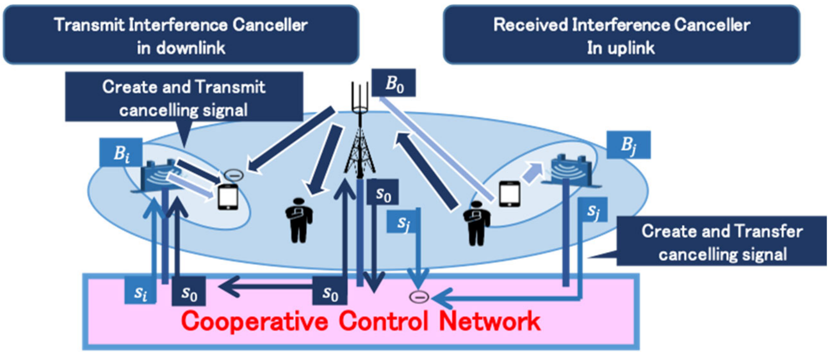
Recent Research Topics

- **3D Layered Cell Construction in Broadband Mobile Communication**
  - Transmit and Receive Interference Canceller for 3D Layered Cell Construction in Broadband Mobile Communication.
  - Vertical plane Power arrival angular profile model for 3D time-spatial path profile model in Broadband Mobile Communication

A Study on Transmit and Receive Interference Canceller for 3D Layered Cell Construction in Broadband Mobile Communication [1][3][4][7][8][11][12]

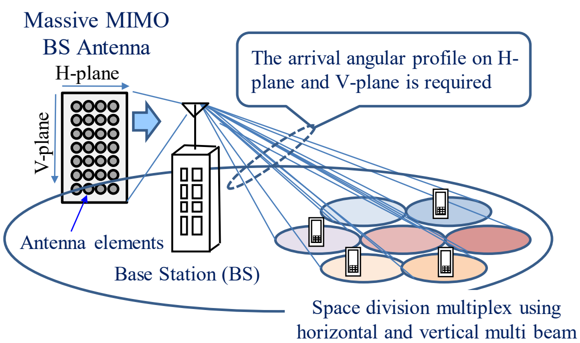
In the three-dimensional(3D) layered cell construction in same frequency bands are used in both macro and small cells, we pioneered interference cancellation technology using “cooperation control network” where each cell cooperates through a network ahead, for LTE and 5th generation mobile communications.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

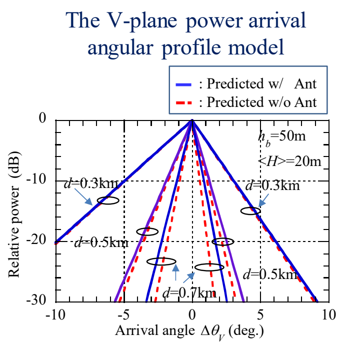
By using these proposed interference cancellers, we showed that the communication quality such as SINR (Signal power to Noise and Interference power Ratio) and communication capacity in small cells can be improved remarkably.



A Study on Vertical Plane Power Arrival Angular Profile Model in Broadband Mobile Communication [6][15]

In order to accurately estimate the performance of spatial processing techniques such as adaptive array antenna (AAA) and multi-input-multi-output (MIMO) for high speed broadband mobile communications, we need a time-spatial path profile model that allows the characteristics of the delay profile and the spatial arrival angular profiles for travelling waves to be simulated at the same time. Especially for spatial processing techniques, such as Massive MIMO, the arrival angular profiles on not only the horizontal plane (H-plane) but also the vertical plane (V-plane) must be modelled. In order to model the arrival angular profile of V-plane, we carried out field measurements in urban and suburban NLOS (Non Line of Sight) environments, and developed V-plane power arrival angular profile model based on measured data. We proposed this model to ITU-R (International Telecommunication Union Radiocommunication sector), This model was standardized in September 2019 as a global standard model Recommendation ITU-R P.1816-4.





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