Mobile Communications Research Group
Tokyo Institute of Technology

2018

ANNUAL REPORT

Contents

Tokyo Institute of Technology 1

Mobile Communications Research Group 2

Laboratory Introduction and Annual Report

- Takada Laboratory 4
- Sakaguchi and Tran Laboratory 12
- Hirokawa Laboratory 20
- Okada Laboratory 28
- Fukawa Laboratory 36
- Aoyagi Laboratory 44
- Nishikata Laboratory 46
- Fujii and Omote Laboratory 48
- Okumura Laboratory 50

Contributions

- Takada Laboratory 52
- Sakaguchi and Tran Laboratory 56
- Hirokawa Laboratory 59
- Okada Laboratory 63
- Fukawa Laboratory 69
- Aoyagi Laboratory 70
- Nishikata Laboratory 71
- Fujii and Omote Laboratory 72
- Okumura Laboratory 73

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 (Hongkan) with "Sakura".

Tokyo Tech Seal

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

Mobile Communication Research Group

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

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

MCRG Members

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

Core Laboratories

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

Cooperate Laboratories

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

Activities

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

Future Communication Research Workshop

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

Open House

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

Takada Laboratory

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

Professor Jun-ichi Takada

Prof. Jun-ichi Takada was born in 1964, Tokyo, Japan. He received the B.E. and D.E. degree from Tokyo Institute of Technology in 1987 and 1992 respectively. 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 is appointed as Vice President for International Affairs in March 2019. 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 is a senior member of IEICE and a member of IEEE.

Specially Appointed Lecturer Azril Haniz

Dr. Azril Haniz received the B.E. degree in electrical and electronic engineering in 2010, and the M.Eng and Dr.Eng. degrees from the Dept. of International Development Engineering in Tokyo Institute of Technology, Japan in 2012 and 2016, respectively. He is currently working as a specially appointed associate professor in the same university. He won the best student paper award in the Singapore-Japan International Workshop on Smart Wireless Communications (SmartCom) in 2014, and is a recipient of the 2016 Tejima Seiichi Doctoral Dissertation Award. He also won the best paper award in ICREST 2019. His research interests include localization, cognitive radio, sensor networks and signal processing. He is currently a member of IEEE and IEICE.

Our Research Interests

Takada Laboratory has been conducting research on the characterization and modeling of the radio propagation channel for wireless communications as well as the application of radio wave technology in various use cases. In particular, research on the radio propagation channel is conducted through extensive channel sounding measurements in various environments (indoor hall environment, urban microcells, subway tunnels, outdoor agricultural fields etc) and various frequency bands (UHF, SHF bands etc). In addition to measurements, simulations of the radio propagation channel are also conducted using several electromagnetic simulation techniques such as ray-tracing, physical optics (PO) and the parabolic equation method.

The use of radio wave technology for various applications is also a main topic of research for Takada Lab. Research on human motion and recognition using radio waves is conducted using measurement data obtained from commercial off-the-shelf Wi-Fi devices, and also through electromagnetic simulations of the human body. Application of radio wave technology for indoor and outdoor localization is also being considered, with hardware implementations using Raspberry Pi devices, and specialized hardware developed by collaborating companies.

Recent Research Topics

- **Channel sounding, propagation channel measurement and modeling**
  - Frequency Dependency Analysis of Clusters in Indoor Hall Environment at SHF Bands
  - Visual Inspection of Scattering Objects for 11 GHz Urban Microcell Channel
  - Superresolution Subspace-based Joint Delay and Angle of Arrival Estimation of Coherent Signals for Millimeter Wave Channel Sounding
  - Research on the Formation of Radio Channel in Subway Train Control System
  - Radio Propagation Channel Analysis and Modeling in Outdoor Agricultural Environments for Wireless Sensor Networks
  - Radio Propagation Prediction in Tunnel using Parabolic Equation Method
  - Path Loss Prediction by Artificial Neutral Network for Wireless Network Cell Planning
  - Channel Capacity Evaluation of Large Array MIMO System from Propagation Parameters based on Directional Channel Model

- **Human motion and gesture recognition using radio waves**
  - Development of Hand Motion Tracking System using Channel State Information from Wi-Fi Devices
  - Studies on Human Motion Recognition through wireless Sensing with Communication Signals

- **Application of radio technology for indoor and outdoor localization**
  - Device-free indoor localization utilizing BLE devices by controlling advertising channels
  - Radio Map Interpolation for Localization of Unknown Radios

Frequency Dependency Analysis of Clusters in Indoor Hall Environment at SHF Bands

(A collaborative research with Aalborg University)

Due to the rapid increase in high data rate applications, 5G wireless systems exploiting several frequencies with large bandwidth have been considered. Frequency dependency analysis and characterization of multipath clusters is necessary as the channel performance depends strongly how they interact with interacting objects (IOs) in the environment, which varies across different frequencies. Thus, this study analyzes the frequency characteristics of clusters at SHF bands with the assistance of physical optics. **Fig. 1** shows the hall environment with the major cluster trajectories, and Table 1 shows the scattering intensities (SIs) of clusters at 3, 10 and 28 GHz bands, in which the cluster power is normalized by the free space at the same distance. Reflection from tube, pillar and elevator was the major mechanism where the clusters are frequency independent, whereas diffraction, scattering and Fresnel zone plate effect from elevator, stud, brick and plasterboard resulted in the various frequency characteristics.

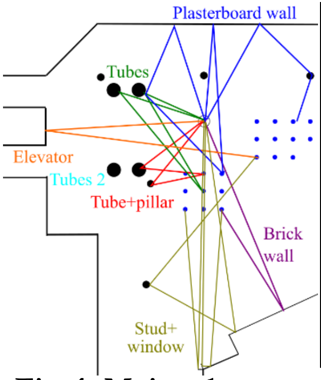


Fig. 1: Major cluster trajectories.

Object	Mechanism	SI mean (dB)		
		3 GHz	10 GHz	28 GHz
Tube	Reflection	-9.7	-9.2	-9.8
Elevator	Reflection, shadowing	-2.1	-2.2	-1.1
	3 GHz zone plate	5.3	0.7	0.9
	28 GHz zone plate	-2.1	-2.1	1.1
Tube+pillar	Reflection	-9.9	-10.6	-10.4
Stud+window	Diffraction	-9.4	-14.3	NA
	10 GHz zone plate	-6.5	-3.3	-8.8
Brick	Scattering	-5.4	-6.8	-10.9
Plasterboard	Scattering	-4.4	-7.3	-9.7
	Shadowing, scattering	-8.9	-13.1	-10.3

Table 1: SI of major clusters.

Visual Inspection of Scattering Objects for 11 GHz Urban Microcell Channel

The frequency bands in the range below 6 GHz are already congested with a limited bandwidth for further use due to the big amount of usage in the wireless services. To satisfy the demand of high data rates, it requires exploring higher frequency with wider bandwidth. At higher frequency, however, the attenuation due to the obstruction of propagation path is more obvious. Considering multiple input multiple output (MIMO) or massive MIMO technology, it is important to characterize the spatial property of the scattered paths for the evaluation of the performance under the line-of-sight obstruction. This study aims at understanding the governing mechanism of the non-line-of-sight propagation paths in a street microcell environment by identifying and characterizing the interacting objects (IO) which are visually identified by superposing the identified paths on to the spherical photo (**Fig.**). Double directional inspections ensure that we find the identical IO from both sides. The software S2 Lite A-GIS can identify the 3D location of the object via a GUI, so that empirical ray tracing is possible between Tx, IO and Rx to calculate the propagation delay time, which then is compared with the measured delay time for further confirmation.

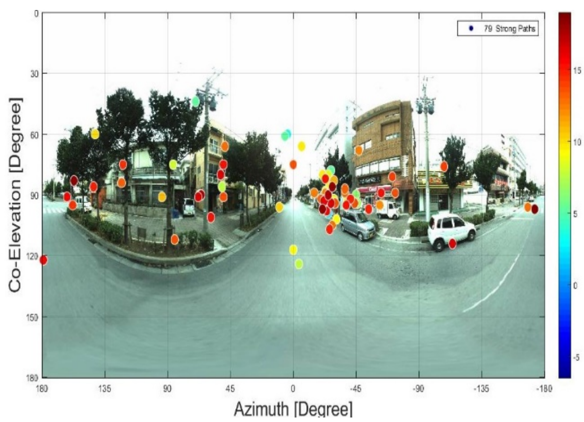


Fig. Spherical view at the Tx and measured paths colored with interaction loss.

Super-resolution Subspace-based Joint Delay and Angle of Arrival Estimation of Coherent Signals for Millimeter Wave Channel Sounding (A collaborative research with NTT)

Measurement campaign was conducted utilizing a 66.5 GHz channel sounder in an anechoic chamber. In order to estimate the parameters of the incoming wave, the subspace-based parameter estimation algorithm, specifically a variant of multiple signal classification (MUSIC) called JADE-MUSIC, is utilized to jointly estimate delay and angle of the multipaths. Accommodating the limitation of the algorithm in the coherent environment with multipaths of the same signal, smoothing preprocessing techniques is done in the frequency domain to decorrelate the incoming multipaths. Measured array response based on the calibration measurement data is also utilized to improve the estimation. The modifications towards JADE-MUSIC that was utilized showed better performance in estimating coherent multipaths.

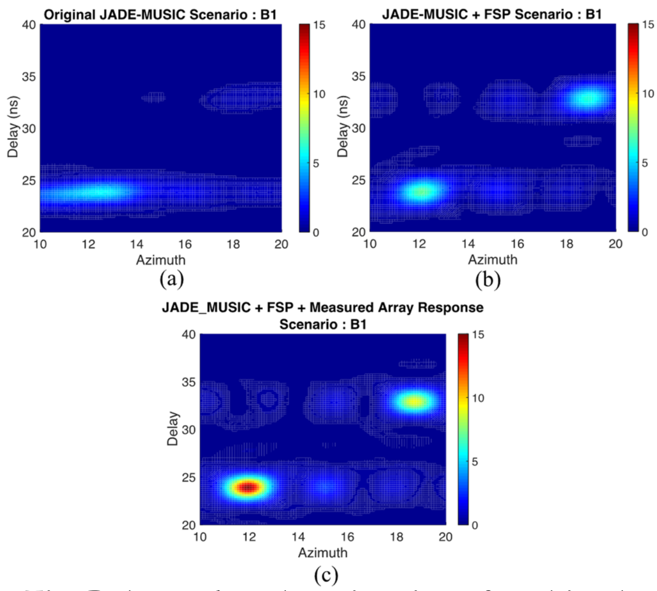


Fig. Delay and angle estimation of multipaths utilizing (a) JADE-MUSIC (b) JADE-MUSIC with FSP (c) JADE-MUSIC with FSP and measured array response.

Research on the Formation of Radio Channel in Subway Train Control System (A collaborative research with Kyosan Electric MFG. Co., LTD.)

Recently, radio communication is introduced for train control based on the advantage that it can simplify way side equipment and maintenance. We are studying three issues for the reliability improvement of the train control system called Communication-based Train Control, CBTC.

(1) Research on the radio wave propagation in a subway tunnel

(2) Research on the radio environment in a railway area, such as stations and way sides

(3) Research on the low rate communication under the congested environment of radio communication

Subway tunnels are rich in curves and slopes compared to high-speed railway tunnels. We would like to use radio waves to achieve better train control communication through research of radio wave propagation and interference. Radio wave propagation measurement campaign was conducted in a subway, and the congestion situation on a platform was simulated. Based on these measurements, we aim at developing a design method for suitable radio base station layout, and a wireless communication system based on analysis from ray-trace simulations and electromagnetic simulations.

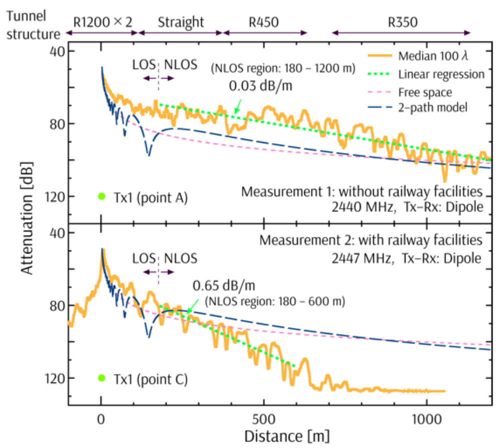
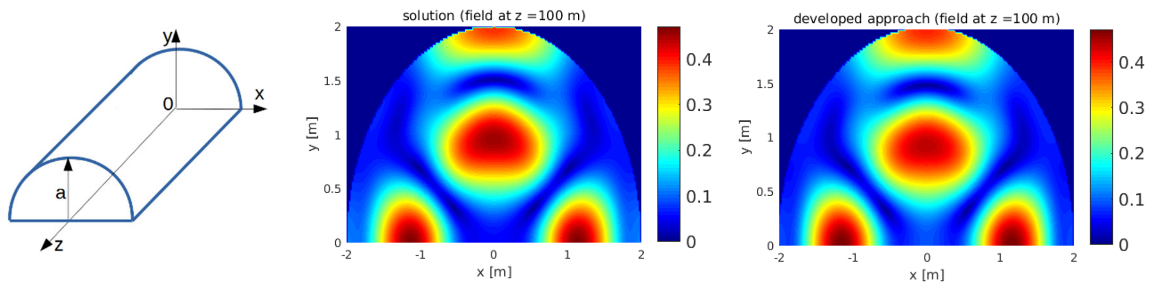


Fig. Radio wave propagation characteristics in a subway tunnel with and without railway facilities.

Radio Propagation Prediction in Tunnel using Parabolic Equation Method (A collaborative research with Kyosan Electric MFG. Co., LTD.)

Controlling the train using wireless communication is an alternative approach to the traditional wire-based approach. The knowledge of radio propagation characteristics in a tunnel is useful for designing such a controlling system. This research developed a radio propagation prediction approach using the Alternate direction implicit Parabolic Equation (ADI-PE) method. By applying the so-called six-points scheme together with the first order interior interpolation technique on the boundary wall of the tunnel, the general matrix form of ADI-PE is obtained. This form can be solved numerically. The figures present one of the validation results in which the developed approach is applied for the straight semi-circular cross section tunnel under the Neumann boundary condition with frequency =3 GHz, a = 2 and mesh size=0.2 λ , 0.2 λ and 5 λ in the x, y and z directions, respectively. It shows good agreement between the developed approach and the analytic solution of the waveguide theory. The agreement is even better if a smaller mesh size is used.



Radio Propagation Channel Analysis and Modeling in Outdoor Agricultural Environments for Wireless Sensor Networks

(A collaborative research with National Electronics and Computer Technology Center, Thailand. This work is partly supported by The Fujikura Foundation)

Information of the radio propagation path loss in an agriculture field is useful for wireless sensor network planning in smart farming. Using the measurement finding that the magnitude of vegetation obstruction causes the variation of the path loss in the field, this research proposed two path loss models for two common types of the tropical agriculture environments; the vegetation obstruction (VO) model for the tall food grass and the equivalent vegetation obstruction (EVO) model for the fruit orchard. Especially, this research developed the approach to determine the equivalent vegetation obstruction by using the electromagnetic simulation. The figures present one of the validation results of the proposed model where the measurement was conducted in a sugarcane field (tall food grass type) with different angular directions. This confirms that the proposed model can represent the measurement results in every angular direction well. Therefore, this model can be used to predict the loss at any point in the field.

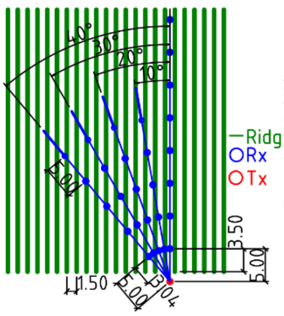


Fig. 1: Part of the measurements in sugarcane field.

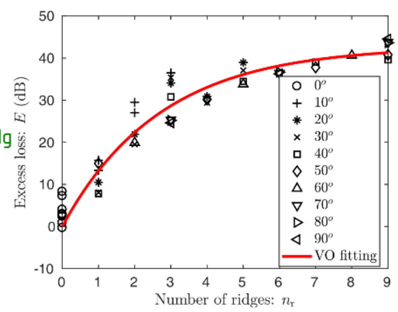


Fig. 2: Measurement result fitted with the VO model in sugarcane field.

Path Loss Prediction by Artificial Neutral Network for Wireless Network Cell Planning (This work is supported by MIC SCOPE No. 185103006)

As global mobile traffic is forecasted to increase, more devices will be connected to wireless networks. We have to deploy more efficient wireless networks to satisfy the growing demands. Path loss information is vital for determination of coverage and optimization efficiency of wireless networks. Therefore we propose path loss prediction model based on artificial neutral network (ANN) and ray tracing (RT) simulations for wireless network cell planning.

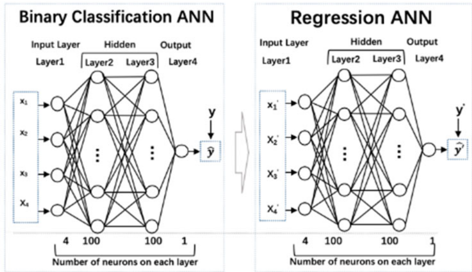


Fig. 1: ANN structure.

Due to constraint conditions in RT simulations, we obtain two types of data, continuous and discrete. Since discrete data is not suitable for directly performing regression, as **Fig. 1** shows we proceed in two steps. We first adopt a binary classification ANN model for predicting whether the receiver is located inside or outside the targeted area, and then we utilize a regression ANN model for estimating path loss only for in-area located receivers. By iteratively utilizing both ANN models we can obtain the path loss distribution for a relatively complicated environment as **Fig. 2** shows.

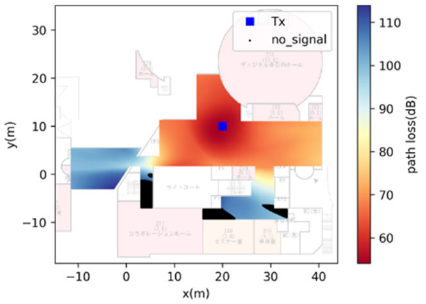


Fig. 2: Path loss distribution.

Channel Capacity Evaluation of Large Array MIMO System from Propagation Parameters based on Directional Channel Model

In recent years, with the spread of various application services using the network, the demand for high speed mobile radio communication system is increasing. In such a system, Multi-Input, Multi-Output (MIMO) transmission aiming at realizing a high data rate has attracted attention as one of the main technologies. Furthermore, because of the congestion in low frequency, we need to utilize higher frequency with large bandwidth. However, the higher frequency will cause shorter propagation range, so the directional channel will be applied to solve this problem. Meanwhile, the directional channel parameter used for the evaluation of the MIMO channel needs to be measured with element spacing of the array antenna being less than half a wavelength, so it becomes a comparatively small array antenna and the angular resolution is also restricted. Therefore, it is not always applicable to large array antennas. From the above, we aim to evaluate the predictable range by predicting the channel response of a large array antenna using the propagation parameters measured by a small array antenna, and compare it with the actual result measured by the large array antenna. Figure shows the eigenvalue percentile result of the measurement and synthesis data. From the figure, we can see a very good agreement between the measurement result and synthesis result.

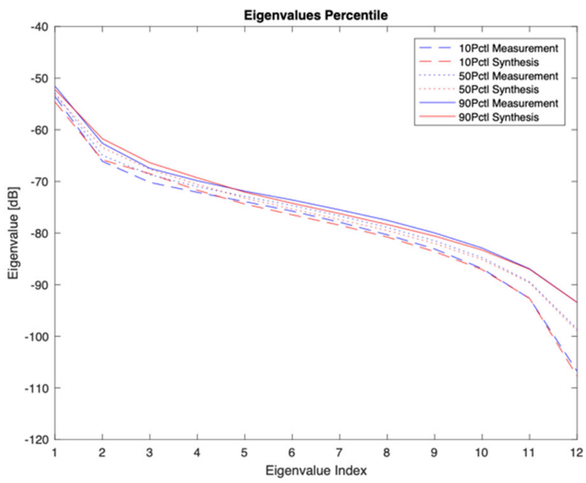


Fig. Eigenvalue percentile of measurement and synthesis data.

Development of Hand Motion Tracking System using Channel State Information from Wi-Fi Devices Calibration of CSI Phase Rotation Utilizing B2B Connection

(This work is partly supported by The Fujikura Foundation)

Wi-Fi has been widely leveraged in RF motion sensing due to its low cost, ubiquitous, and easiness to deploy. In the presence of any motion, the phase component of channel state information (CSI) will experience temporal rotation due to the change of propagation delay, and this phenomenon is the key to sense the motion. In practice, however, the time-varying frequency offset of local oscillators (LOs) between two Wi-Fi transceivers due to the absence of synchronization obscures the CSI phase. Therefore, it is virtually impossible to realize motion analysis without acquiring the parameters that cause this undesired rotation from Wi-Fi chips.

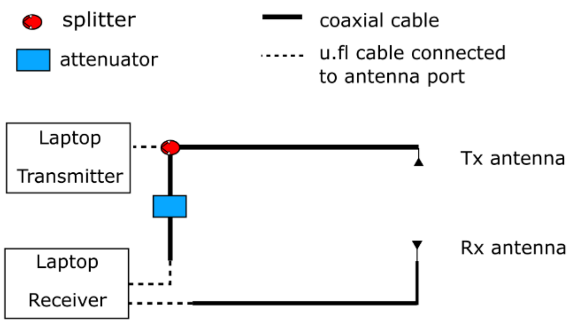


Fig. 1 × 2 SIMO configuration of the proposed b2b calibration.

Our work introduces the use of a back-to-back (b2b) channel as the reference CSI to effectively suppress the phase rotation without contaminating the target CSI itself. An experiment was performed to compare the calibrated CSI with the channel measured using a Vector Network Analyzer as ground truth. The results have successfully shown similarity of the CSI phase component relative to the ground truth albeit with the constant residual phase offset. After removing the constant residual offset, the CSI phase closely resembled the ground truth with 0.117 radians root mean square error (RMSE).

Studies on Human Motion Recognition through wireless Sensing with Communication Signals

Electromagnetic signals from communication devices can be also used for wireless sensing. This potentially leads to contact-less, device-less, camera-less applications of human motion recognition by ubiquitous radio frequency (RF) sensing. However, the time-variant physical phenomena of RF scattering from deformable biological human bodies are complicated, which depend on many factors such as shape, material properties, polarization, geometry, etc. And there is a lack of extensive data for analysis because it is difficult and costly to get by measurement. In this research, physically plausible large data is generated. This deterministic and flexible simulator uses inputs of measured motion data, generative human models in various postures, and a numerical EM high frequency asymptotic method of physical optics (PO). Results shows the importance of doppler signature and the geometry dependent nature of RF sensing, and a simple classifier can be built with inputs of such time-frequency spectrograms.

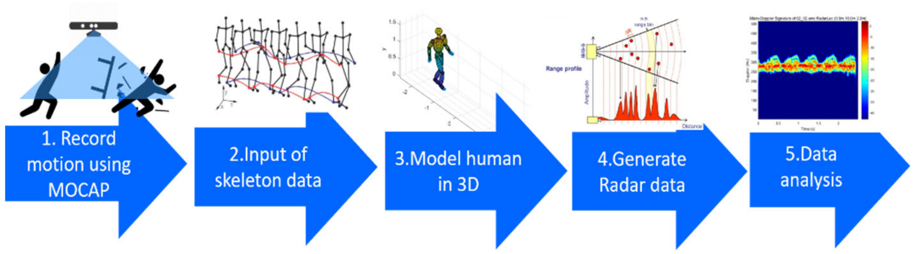


Fig. Methodology.

Device-free indoor localization utilizing BLE devices by controlling advertising channels

Recently indoor localization systems have become a focus of research and development. In this research, a device-free indoor localization system by utilizing Raspberry Pi2 is established. The fingerprinting technique is employed. In our proposed system, the Received Signal Strength Indicator (RSSI) of Bluetooth Low Energy (BLE) signals are used as location fingerprints. BLE is a narrow band communication system and transmits advertising packets on three different frequency channels. In conventional approaches, the RSSI from each frequency channel is not individually considered, thus it may suffer from large fluctuations, resulting in low localization accuracy. Therefore, in this study, two methods are utilized to employ channel specific features. First, the device is controlled to transmit advertisements on one pre-set advertising channel. Second, all the advertisements with known channel numbers are received one by one. Thus, we can have triple features at one position's fingerprint, resulting in possibly better localization accuracy. Experiments were conducted in office environment and results showed that combining of all the advertising channels with their channel numbers can achieve better results.

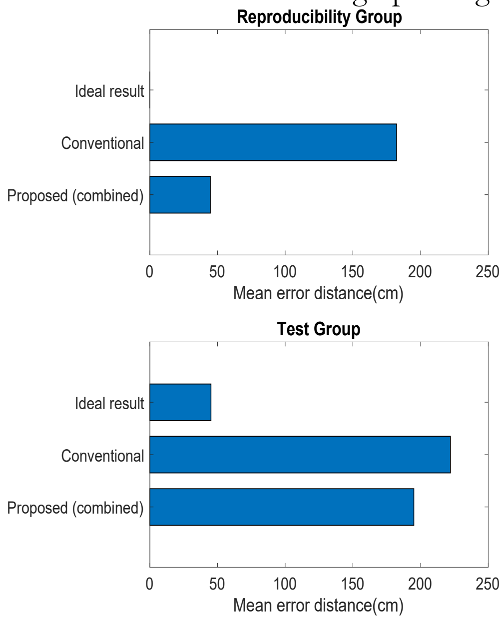


Fig. Localization accuracy of proposed system.

Radio Map Interpolation for Localization of Unknown Radios
(A collaborative research with Koden Electronics Co., Ltd.)

Conventional localization based on radio maps, also known as fingerprinting, is only reliable in scenarios where the center frequency of the target radio is the same as that used when constructing the radio map. However, for unknown radios, it is very unlikely that the precise center frequency used is known in advance. In order to address this issue, a novel approach to interpolate the radio map is proposed in this research. Firstly, the RSS radio map is measured at multiple frequencies, and hardware architecture which can support the sequential measurement of a multi-frequency radio map is also proposed. Then, a novel algorithm is employed to interpolate the radio map in the frequency and spatial domains, based on the log-linear frequency characteristics and spatial correlation of the RSS, respectively. In order to evaluate the proposed algorithm, a measurement campaign was conducted in the Tokyo Tech O-okayama campus area. The radio map measured at two different center frequencies was used to predict the radio map at 1297MHz. Results showed that the proposed algorithm could achieve a RMSE (root mean squared error) of about 2.5dB on average, which led to an improvement of localization accuracy by about 5m.

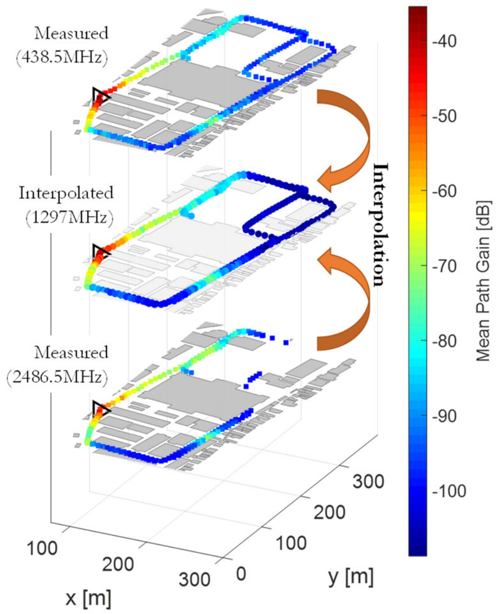


Fig. Measured and interpolated radio maps in O-okayama campus.

Sakaguchi and Tran Laboratory

Home page: https://www.sakaguchi-lab.net/

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 Professor and at the same time he is a Senior Scientist at Fraunhofer HHI in Germany. 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. He served as a TPC co-chair in the IEEE 5G Summit in 2016, a General co-chair in the IEEE WDN-5G in 2017, and an Industrial Workshop co-chair in the IEEE Globecom in 2017. His current research interests are in 5G cellular networks, millimeter-wave communications, and wireless energy transmission. He is a member of IEICE and IEEE.

Assistant Professor Gia Khanh Tran

Assist. Prof. Tran received the B.E., M.E., and D.E. degrees in electrical and electronic engineering from Tokyo Institute of Technology, Tokyo, Japan, in 2006, 2008, and 2010, respectively, where he is currently an Assistant Professor. His research interests include signal processing, multiple-input multiple-output mesh networks, coordinated heterogeneous cellular networks, millimeter-wave communication, and localization. He received the IEEE VTS Japan Young Researchers Encouragement Award from the IEEE VTS Japan Chapter in 2006 and the IEICE Service Recognition Awards in 2013 and 2015. He also received the Best Paper Award in Software Radio from the IEICE SR technical committee in 2009 and 2013, the Best Paper Award at SmartCom2015, and the Best Paper Awards from both IEICE and IEICE ComSoc in 2014. He served as a Technical Program Committee co-chair in a series of IEEE WDN workshops, including WDN-5G in ICC2017.He is currently the Assistant of the technical committee on Smart Radio of the IEICE ComSoc. He is a member of IEEE.

Emeritus Professor Kiyomichi Araki

Prof. 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 life member of IEEE, and fellow of IEICE.

SAKAGUCHI LAB's Recent Research topics:

- **5G cellular networks (5G)**
  - Millimeter-wave overlaid heterogeneous networks
  - Millimeter-wave edge cloud with prefetching
- **Millimeter-wave mesh network**
  - Flexibly configurable millimeter-wave meshed networks
  - Test-bed construction based on SDN technologies
- **Wireless sensor networks and its applications**
  - Fingerprint-based automated driving robots
  - Battery-less sensors activated via wireless power transmission

Sakaguchi and Tran Laboratory

mWave Edge Cloud for 5G Cellular Networks

Background

In recent years, the demand for further expansion of the capacity of wireless communication is increasing due to the drastic growth in the number of connected devices and the emergence of various service applications. Currently, the trend towards 5G system introduction in 2020 is becoming active. The typical usage scenarios of 5G have been identified as eMBB, mMTC, and URLLC. Meanwhile it is necessary to decrease traffic on the backhaul side and reduce the end-to-end latency. To address it, in the last few years, we have proposed the concept of mmWave overlaid heterogeneous cellular networks where mmWave small cell base stations are introduced into the conventional macro cells as shown in Fig.1.

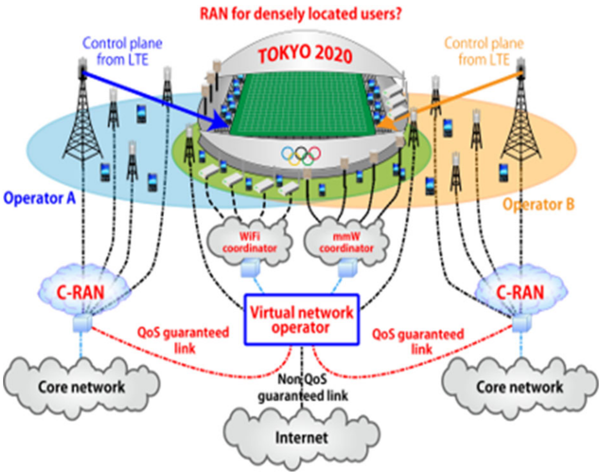


Fig. 1. 5G Cellular Network.

Moreover, we attempt to introduce a new concept based on the combination of ultra-broadband mmWave communications and multi-access edge computing (MEC) as a solution.

System Architecture for mmWave Edge Cloud

The mmWave Edge Cloud system architecture is shown in Fig.2. As an overview of this architecture, the cloud side applications are also deployed on the MEC side according to the application requirements and data traffic situations, and the users are controlled with out-of-band C-plane to be connected to the surrounding MEC application. To reduce the backhaul traffic and end-to-end latency, our architecture could be realized by forwarding (prefetching) data to an edge cloud based on users and network context information such as user position, network load, and data popularity, and enables the network to orchestrate its radio and MEC resources.

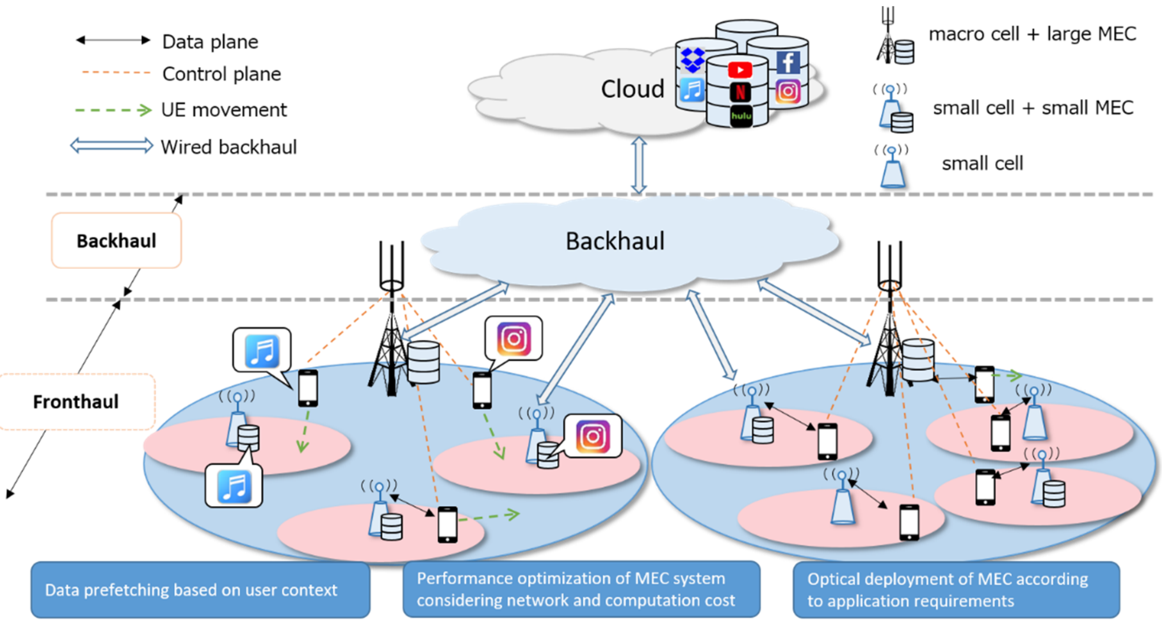


Fig. 2 mmWave Edge Cloud System Architecture.

Proof of Concept for 5G mmWave Edge Cloud [10]

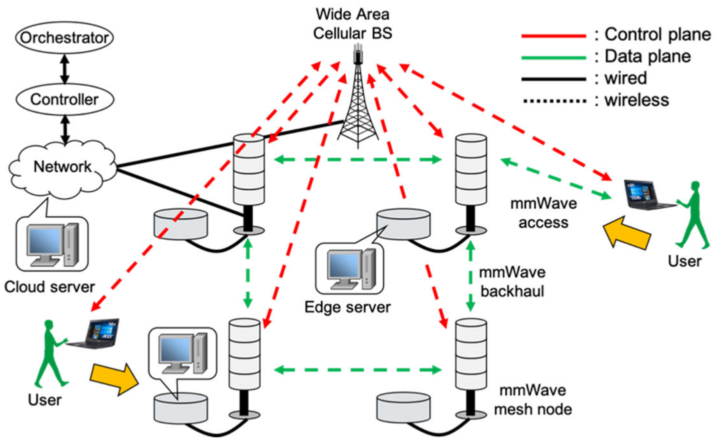


Fig. 3 Abstract of mmWave edge cloud.

In recent years, ultra-broadband communication using densification of millimeter-wave (mmWave) smallcell base station has attracted attention owing to its ability to accommodate increasing mobile data traffic. To make full use of mmWave access, deploying ultra-broadband backhauling lines such as optical fibers everywhere is an extremely expensive approach. mmWave meshed network is therefore a cost-efficient wireless backhaul architecture for mmWave overlay cellular network. Owing to its wide bandwidth and flexibility in link connection via beam steering and multi-hop relay, mmWave meshed network is furthermore suitable for dynamic construction of backhauling in adaptation to change of user traffic's distribution via adaptive allocation of backhaul resources of densely co-located users (UE). On the other hand, as UE nowadays wants to experience services everywhere without disruption even when moving, it is desirable that UE-specific multimedia contents are located as close as possible to the UE via Multi-access Edge Computing (MEC) technology. Covering all the above requirements, we construct a real UE-centric edge content delivery system in which content server is re-located in adaptation to UE's context information e.g. location, via dynamic routing over mmWave meshed backhaul network, enabled by Software Defined Network (SDN) technology. We call the system mmWave edge cloud. Using our developed WiGig device based testbed, outdoor experiment campaign is conducted in the Tokyo Tech university campus. Fig. shows the abstract of mmWave edge cloud. The testbed is composed of four mesh nodes PC attaching mmWave access, mmWave backhaul and WiMax router. A picture of the actual node is shown in Fig. . The access and backhaul confirm to the IEEE 802.11ad standard at 60Hz band and can achieve Gbps communication speed. The nodes have server virtualization engine so that virtualized server can be deployed at any edge nodes flexibly. In addition, there are SDN controller and orchestrator outside the LAN, and context information is collected from UE, and based on it, commands such as backhaul link formation and virtualized server migration are sent to nodes using the WiMax channel and executed automatically. As a result, the server is always deployed at a node close to UE, so that user can experience high-speed and low-latency services that make full use of mmWave access performance. Table 1 shows a comparison of the latency between patterns without MEC and with MEC.

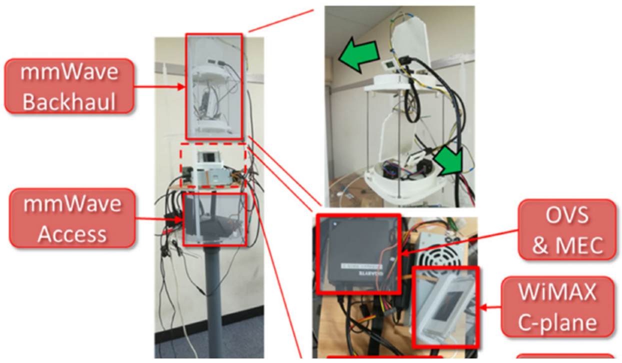


Fig. 4 Picture mmWave mesh node.

Table 1 Latency of w/o MEC and w/ MEC

Pattern	Latency [ms]
w/o MEC	≃4
w/ MEC	≃0.5

Sakaguchi and Tran Laboratory

Millimeter-wave Mesh Backhaul Networks [10], [11], [14], [17]

Introduction

5G communication network is expected to support enhanced mobile broadband services by millimeter-wave overlay heterogeneous network (HetNet). However, connecting backhaul using cable such as optical fibers is extremely costly. To circumvent, we have proposed mmWave mesh backhaul networks (MMBN). MMBN shown in **Fig. 5** enable centralized software defined network (SDN) control using LTE macro cell base station in order to determine relay route, dynamic ON/OFF and etc.

One of the problems toward realizing MMBN is intra-channel interference from other links, so we need interference management to obtain high backhauling rate. As a contribution to solve this problem, we proposed interference management for MMBN.

Proposed Algorithm

In order to adapt to intensive user traffic distribution, we design the networks to achieve maximum throughput until the furthest link. In order to achieve the requirement, we proposed a 3-step approach of deploying mmWave Access Point (AP) in zigzag, allocating orthogonal channels when necessary and finally optimal power transmission allocation for alleviating bottleneck of the mesh backhaul networks. However, the number of dynamic searches increases rapidly when we combine these methods. Therefore, we first employ static allocation exploiting characteristic of mmWave and then dynamic allocation using simple approaches. Our algorithm is shown in **Fig. 6**.

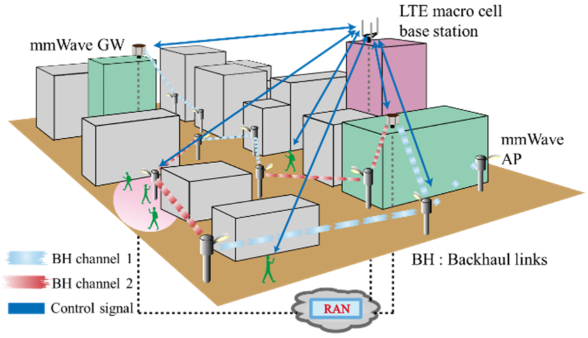


Fig. 5: MMBN architecture.

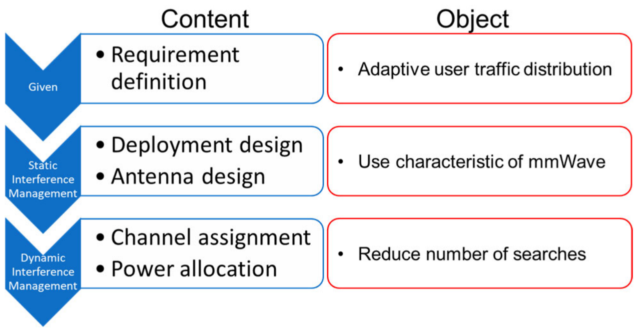


Fig. 6: Algorithm of interference management.

Simulation Analysis

Figure 7 shows that coverage using the proposed algorithm is improved as compared to conventional approach which deploys APs linearly and alternates channel per hop. We confirmed the proposed approach can reduce interference up to 250m from mmWave GW and the number of dynamic searches reduces significantly shown in **Fig. 8**.

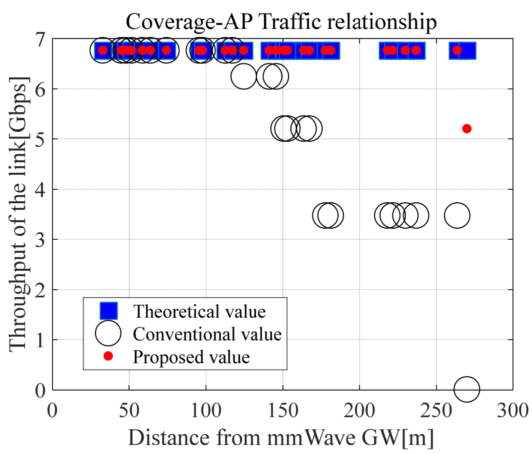


Fig. 7: Coverage characteristic.

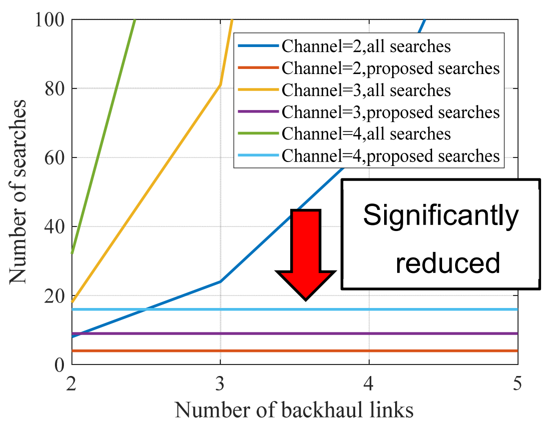


Fig. 8: Number of dynamic searches.

Super-High-Resolution Environment monitoring using drone

Thanks to recent advancement of vehicular technology, unmanned aerial vehicles(UAVs), also called drones, have become one of the most promising technologies to contribute to people's future daily life. Drones can be utilized for various applications, such as video monitoring, surveillance, delivering items, rescue operation and so on, among which the super-high-resolution video monitoring using drone footage is especially attracting the most attention.

The real-time transmission is required in many application scenarios, such as live sports broadcast and monitoring. In common video transmission schemes, the encoding and decoding is employed duo to the limited bandwidth, but this process also causes large transmission delay. Therefore, to address it, we proposed the super-high-resolution uncompressed video transmission from drones using 60GHz band, as is shown in **Fig. 9**. Delay time is shortened by omitting the encode and decode. Also, capacity data like super definition uncompressed video data.

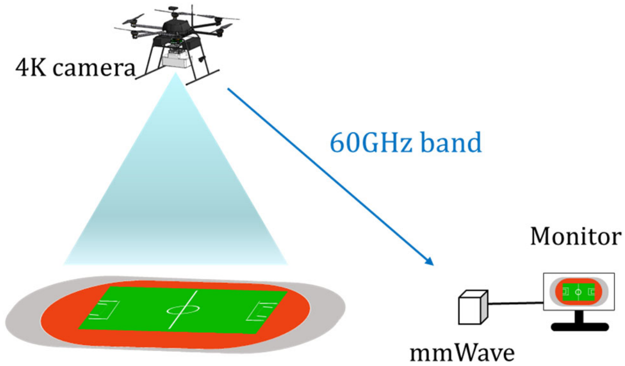


Fig.9.Monitoring using drone.

Fig.10. Flying drone

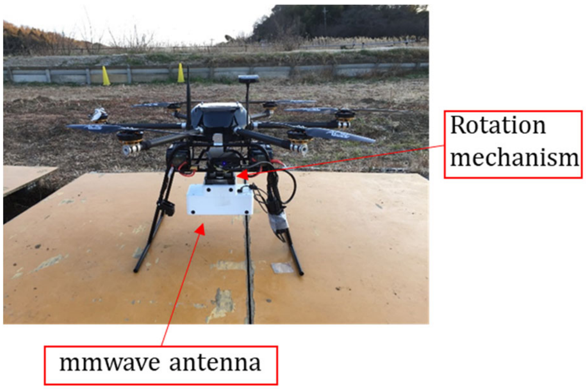


Fig.11. Drone loaded mmwave antenna.

Figure 10 shows the drone which is flying and transmitting the capturing video through 60GHz mmWave communication.

Figure 11 shows the configuration of the drone equipped with the mmWave antenna and a mechanical rotator in the outdoor experiment. In the outdoor experiment, we flew the drone perpendicularly to ground station and transmitted the uncompressed 4K video.

Fig.12. Drone footage from 80m.

Figure 12 shows the drone footage view from the air. We succeeded in transmitting real-time uncompressed 4K video up to 100m in the sky.

Experiment Video can be seen in the URL below
https://youtu.be/L7OfRoHZ9jE

Sakaguchi and 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.

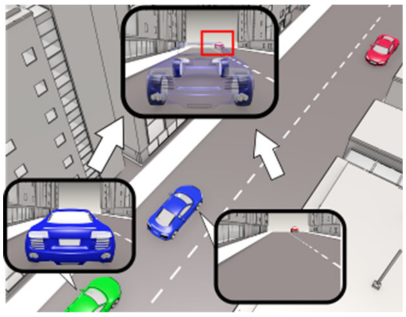


Fig. 13 Concept of cooperative perception.

mmWave V2X for Cooperative Perception

The cooperative perception's communication requirement is still an open question. Current vehicular communication standards and frequency bands are not insufficient for the huge amounts of data from onboard sensors, and the millimeter-wave communication is expected to be a strong candidate because of its wide bandwidth and large communication capacity. **Fig. 14** is derived from the typical overtaking scenario, and shows the relation between required sensor data rate to detect the oncoming vehicle and the feasible channel capacity at each carrier frequency. It can be concluded that the millimeter-wave communication with cooperative perception is able to effectively increase the driving safety and allows vehicles to safely overtake at 51 km/h.

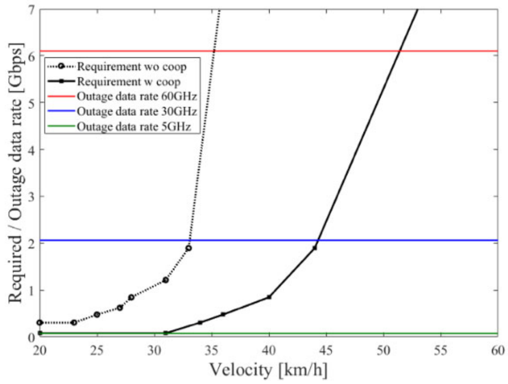


Fig. 14 The relation between channel capacity and required data rate.

Testbed Development

The hardware prototype as the Proof-of-Concept of mmWave vehicular communication for the cooperative perception and automated driving has been developed. The hardware structure is illustrated in **Fig. 15**. The moving robots (Kobuki) equipped with LiDAR sensors, mmWave APs, and onboard controllers act the automated driving vehicles, and they share the sensor data with other robots through the mmWave data plane. All sensor data flows and link connections in the mmWave data plane are controlled by the SDN controller based on the real-time context information (e.g., position, orientation, channel status) of the robots through a Wi-Fi network which acts the control plane.

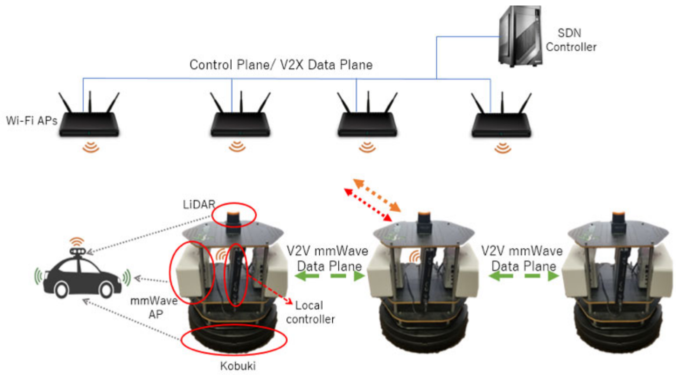


Fig. 15 Architecture of cooperative perception.

Wireless Energy Transmission and Battery-less Switch

The limited battery lifetime and maintenance works of recharging of sensor nodes has long been issues in wireless sensor networks, and greatly constrained their practical applications. In order to address the problem, we proposed a wireless grid, in which battery-less sensor nodes can be activated by the multi-point wireless energy transmissions (WET) with carrier shift diversity, which can archive seamless energy supply in the target office. And it has been practically implemented in one office of Sakaguchi Lab, Tokyo Tech. The experiment results in **Fig.17** confirm that the coverage for the sensor activation is 100%.

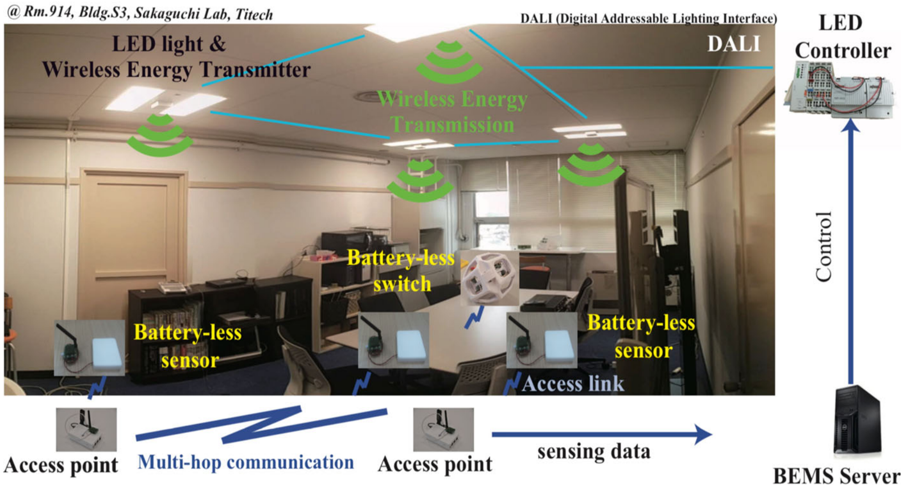


Fig. 16 Wireless energy transmission system and the lighting control system.

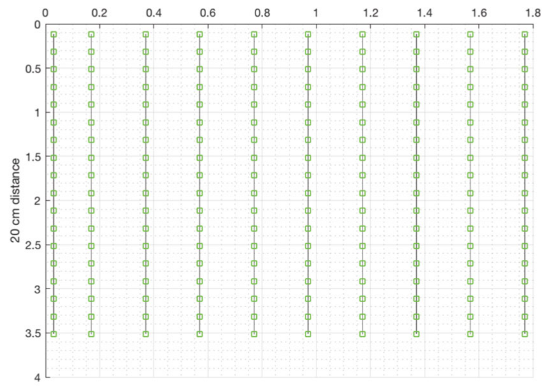


Fig. 17 Coverage of the wireless energy transmission.

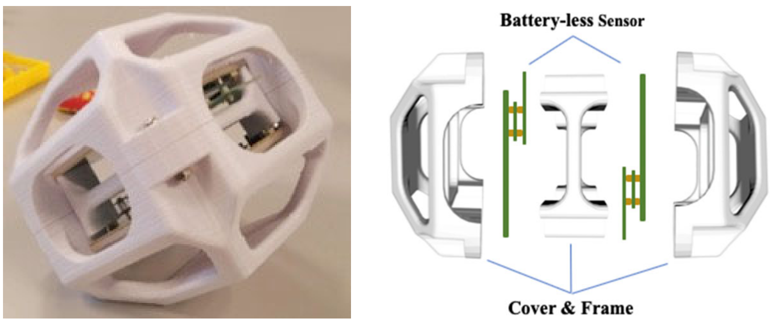


Fig. 18 Battery-less switch and its structure.

As an application of WET and building energy management, as illustrated in **Fig.1**, an automatic office lighting system controlled by battery-less switches is designed and implemented. The lights' all actions (e.g., turn on/off, dim up/down, change colors) are controlled by the different laying angles of the switch, which is battery-less and activated by the wireless energy transmitters from the ceiling. **Fig.18** shows the switch's sandwich-structure, and its frame and covers are all 3D-printed. One switch has two back-to-back battery-less sensors, whose design is shown in **Fig.19**, in order to ensure that the rectennas can receive energy from omni-directions. The battery-less sensors sense the angles and transmit the data to the controller through multi-hop wireless communications because of the limited power.

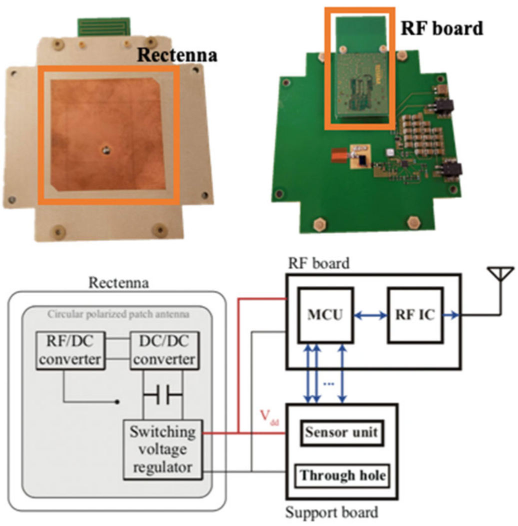


Fig. 19 Battery-less sensors.

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.

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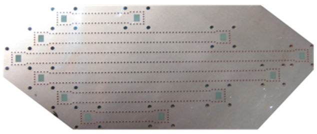
received the B.S., M.S. and D.E. degrees in electrical and electronic engineering from the Tokyo Institute of Technology, Tokyo, Japan, in 2008, 2011 and 2014, respectively. He was a Research Fellow of the Japan Society for the Promotion of Science (JSPS) in 2013. From 2014 to 2017, he worked at Mitsubishi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

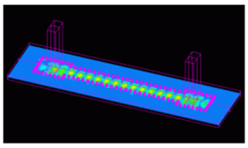
Dr. Tomura received the Best Student Award from Ericsson Japan in 2012 and the IEEE AP-S Tokyo Chapter Young Engineer Award in 2015 and Young Researcher Award from IEICE technical committee on antennas and propagation in 2018. He is a member of IEEE and IEICE.

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.

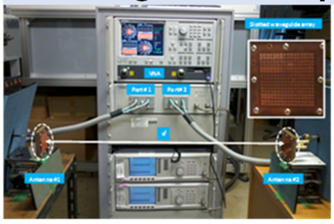
Post-wall waveguide

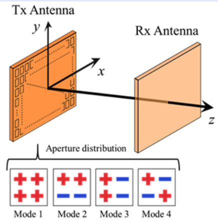




- Known as Substrate Integrated Waveguide (SIW)
- Published in the IEEE transaction in 1998 (Total citation: 308, Web of Science, 2017/6)
- Used as microwave and millimeter-wave band low-loss waveguide

Rectangular coordinate orthogonal multiplexing (ROM)

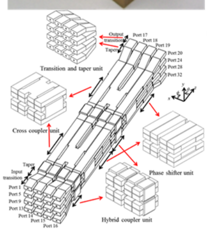




- Published in the IEEE transaction in 2017
- Equivalent to OAM transmission in the optical communication system, and apply to microwave and millimeter-wave applications

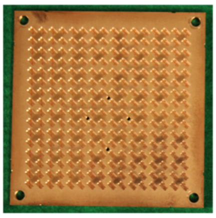
2-D beam-switching one-body Butler matrix

- 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)

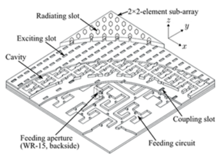


- $4^2 \times 4^2$-way one-body 2-D beam-switching waveguide Butler matrix
- Reduced its length and conduction losses by half.
- Reduced the number of components and volume.

Corporate-feed Slot Array Antenna with Plate-laminated Waveguide

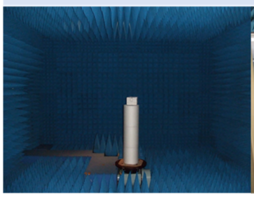


- Published in the IEEE transaction in 2011.
- After that, research is also started in Sweden, Singapore, China, etc.
- Designed in various frequency bands like 38-GHz band, 60-GHz band, and 120-GHz band, etc.

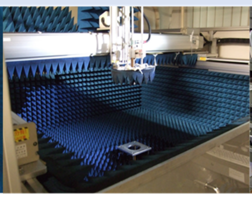


✓ Large number of elements
⇒ High gain
✓ Made with metal only
⇒ High efficiency
✓ Composed of the corporate-feed circuit
⇒ Wide band

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

Design of a 2×2-Element for a Perpendicular-Corporate Feed Four-layer Parallel-Plate Pair-Slot Array Antenna

We have proposed a perpendicular-corporate feed in a three-layer parallel-plate slot array. This antenna structure enables the complete removal of the x-shaped cavity walls in the radiating part of conventional planar corporate-feed waveguide slot array antennas. Instead of cavities, the proposed antenna has a dielectric layer with adequate permittivity in the region between the coupling-aperture layer and the radiating-slot layer so that the region can generate standing waves strongly for a large number of slots. To enhance the VSWR bandwidth, we have placed a parasitic-slot layer over the radiating layer with an air gap in between and then an additional-slot layer over the parasitic-slot layer with an air gap in between. This structure also results in avoiding metal contact in the radiating part. however, it includes higher sidelobes caused by higher modes in the 45^{o} plane due to the wider slots of the additional slots. This paper presents the design of a 2×2-element subarray for a 16×16-element perpendicular-corporate feed four-layer parallel-plate pair-slot array antenna. To suppress sidelobes in the 45^{o} plane, we introduce pair-slots in the additional-slot layer. This leads to lowering sidelobes, remaining the wideband characteristic of the VSWR. We reveal the effect of pair slots in the proposed antenna.

Fig. 1 shows the analysis model of the 2×2-element subarray. The antenna consists of the additional pair-slot layer, the parasitic-slot layer, the radiating-slot layer, the dielectric layer, the coupling-aperture layer, and the feeding-waveguide layer. There are air gaps between the slot layers including the coupling-aperture layer, and so there are no metal contacts in the radiating part. The dielectric layer consists of polytetrafluoroethylene (PTFE), with $\varepsilon_r = 2.17$, and an air layer to achieve the desired permittivity. The spacing of all the slot types is constant: $0.86\lambda_0$ (4.20 mm) in the x and y directions, where the λ_0 is the wavelength at the design frequency of 61.5 GHz.

In the analysis, we use a dielectric layer of $t_d = 0.38$ mm and $\varepsilon_r = 2.17$. The conductivity 5.8×10^7 S/m of copper and a loss tangent 0.0006 of the dielectric are assumed. For the frequency characteristic of the reflection, the reflection with pair slots is smaller than −14 dB over 13.0 % of the bandwidth ranging from 57.5 to 65.5 GHz. This result is almost equal to that of no pair slots. For radiation patterns at 61.5 GHz, In the E plane, the pattern for pair slots is in good agreement with that for no pair slots except around ± 35^{o} regions. Sidelobes in the regions are caused by excitation difference in the x direction of the 2×2-element subarray based on the introduction of the pair slot. The sidelobe level is small: less than −23 dB. In the H plane, the pattern for pair slots is in good agreement with that for no pair slots. In the 45^{o} plane, the pattern for pair slots has lower sidelobe level than that for no pair slots around the ± 55^{o} regions. The level is improved from −21 dB to −38 dB. We confirmed the effect of pair slots in the 45^{o} plane. For the frequency characteristic of realized gain, the realized gain for pair slots is 33.6 dBi at 61.5 GHz, higher than that for no pair slots 33.4 dBi. The antenna efficiency for pair slots is almost 95 % higher than that for no pair slots 90 %, ranging from 58.0 to 65.0 GHz. The improvement of sidelobes in the 45^{o} plane enhances the realized gain and the antenna efficiency.

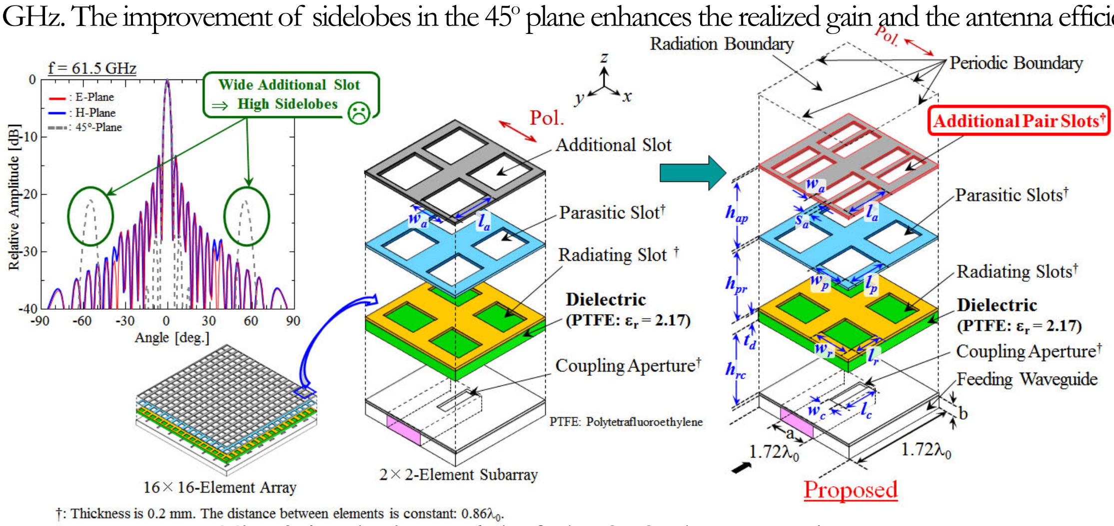


Fig. 1 Analysis model of the 2×2-element subarray.

Referrence

[1] H. Irie, and J. Hirokawa, "Perpendicular-corporate feed in three-layered parallel-plate radiating-slot array," *IEEE Trans. Antennas Propag.*, vol. 65, no. 11, pp. 5829 - 5836, Nov. 2017.
[2] H. Irie, T. Tomura, and J. Hirokawa, "Design of a 2×2-Element for a Perpendicular-Corporate Feed Four-layer Parallel-Plate Pair-Slot Array Antenna," Proc. of International Symposium on Antennas and Propag. (ISAP), A10_1001, Busan, Korea, Oct. 23-26, 2018.
[3] T. Tomura, J. Hirokawa etc., *IEEE Trans. Antennas Propag.*, vol. 62, no. 10, pp. 5061 – 5067, Oct. 2014.

Suppression of E-plane Sidelobes using Double Slit-layers in a Corporate-feed Waveguide Slot Array Antenna consisting of 2×2-element Radiating Units

The double-layer corporate-feed waveguide slot array antenna shown in the bottom of Fig.1 was proposed for a wideband high-efficiency planar antenna in the millimeter-wave band. When we apply Taylor distribution where the first sidelobe level = -25 dB and $\bar{n}$ = 5 in the aperture field distribution to suppress the sidelobe level, the sidelobe level in the tilted directions around 30-40 degrees is increased to about -22.6 dB because the 2×2-radiating slots are excited equally in each unit sized by 1.66 wavelengths. This paper proposes a new structure by adding double slit-layers to the conventional structure to suppress the sidelobes in the E-plane. The design frequency is 73.5 GHz.

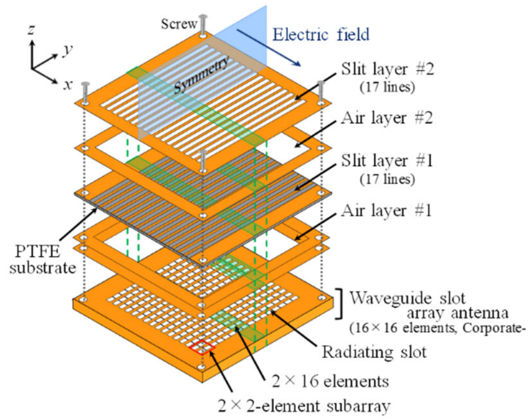


Fig. 1 Antenna structure.

Fig.1 shows a corporate-feed waveguide slot array antenna with double slit-layers. The electric field is oriented in the x-direction. The proposed antenna has a PTFE substrate with 17 lines as the slit layer #1 (thickness: 0.018 mm) through air layer #1 on the 16×16 slots array, and the slit layer #2 with 17 lines (thickness : 0.2 mm) through air layer #2 on the slit layer #1. The radiating slots has a constant spacing d in the x- and y-directions. The slit spacing is also d in the x-direction. The radiating slots and the slits are shifted by d/2 in the x-direction. The PTFE substrate is introduced in the region between the radiating slots and the slit layer #1 in part so that the effective wavelength becomes twice the slit spacing in the x-direction for averaging the excitations of adjacent radiating slots. Slit layer #2 acts as reflection suppression in the double slit-layers in the z-direction by proper spacing from the slit layer #1. As a result, the 8.8% bandwidth of VSWR less than 1.5 is achieved. The sidelobe level of the tilted directions around 30-40 degrees is suppressed to -30.0 dB from -24.7 dB at the design frequency.

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Design of an 112×64-element Corporate-feed Hollow-waveguide Slot Array Antenna

We proposed corporate-feed waveguide slot array antennas which have wide bandwidth in the 60GHz-band (57-66GHz). Previously, this antennas were only a $2^n \times 2^m$-element array, where n and m are integers. There is a demand designing the large array-size of this antenna for the 60GHz-band compact range wireless system and achieving more high gain antennas. When we increased or decreased an array-size conventionally, we had ever been only able to change the elements to 2^n or 2^{-n} (ex. ···32↔64↔128↔256↔512···). Thereby, an array-size change in large antennas has a lower flexibility than that in small antennas. Therefore, we propose a 112×64-element (not $2^n \times 2^m$-element) array antenna which combines a 56×32-division circuit and 2x2 circularly polarized radiating elements.

A 56×32-division is a $7 \cdot 2^3 \times 4 \cdot 2^3$-division. A $2^3 \times 2^3$-division circuit could use the conventional structure which was corporate-feed without depending on frequency in principle because of the structural symmetry in the power division. By contrast, a 7×4-division circuit is corporate-feed with frequency dependence because it includes asymmetric circuits in part. Twenty-eight (7×4) $2^3 \times 2^3$-division circuits are located at the end of feeding circuit, and connected to the input through a 7×4-division. Furthermore, the $2^3 \times 2^3$-division circuits are located in the upper layer and the 7×2^2-division circuit is located in the lower layer. Thereby, it is sufficient to corporate-feed the lower layer (7×4-division circuit) for corporate-feeding the 56×32-division circuit. As illustrated in **Fig. 1**, the 7×4-division circuit includes asymmetric T-junctions in part to arrange a desired magnitude distribution ratio at all output ports. Thereby, the phase difference among all the output ports generates from the structural difference between the T-junction (red) and the H-bend (blue) and from the asymmetric T-junctions. We control the output phase by using a structure of the 7×4-division circuit as illustrated in **Fig. 1**.

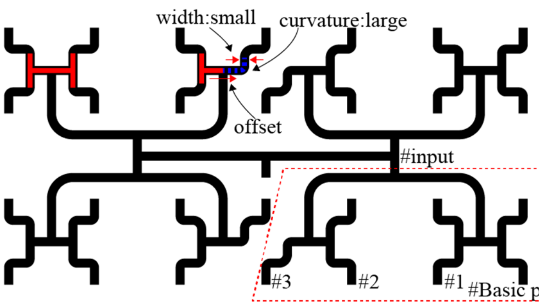

Fig. 1 7×4-division feeding circuit structure.

In the 60GHz-band, the maximum error at the ends of the 56x32 feeding circuit is less than 0.7dB in amplitude and 5.5deg. in phase. The excitation in the feeding circuit is almost uniform in the 60GHz-band. The 112x64-element array antenna consists of the 56x32 division feeding circuit and the 2x2 circularly-polarized radiating elements. VSWR of this antenna is below 1.5 in the 60GHz-band.

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Design of a Dual-polarized Slot Array Antenna with Monopulse Corporate-feed Waveguides for Two-dimensional Orthogonal 8-multiplexing in the Non-Far Region

A multiplexing transmission antenna using two-dimensional orthogonal phase distribution in the rectangular coordinate system, which is equivalent to OAM transmission based on that in the cylindrical coordinate system, has been proposed. It can radiate four ortho
gonal beams in the same direction with the same frequency in the line-of-sight environment. This antenna system was experimented and the channel capacity increased up to fourfold compared to a SISO (Single Input Single Output) system around 78.5GHz. The authors propose a dual polarization of this multiplexing antenna system by using a dual-polarized waveguide slot array antenna. We design an 8-multiplexing 16x16-slot array antenna with uniform excitation in the 60GHz band.

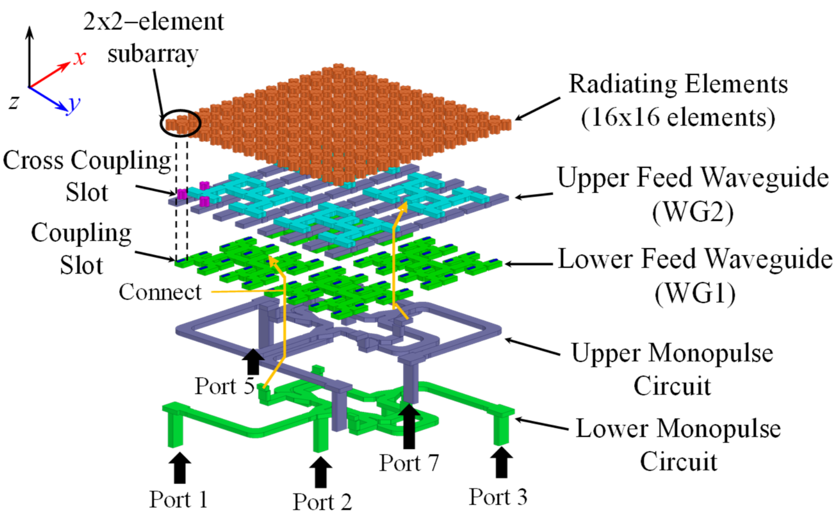

Fig. 1 Antenna structure.

Fig. 1 shows the proposed 16x16-slot array dual-polarized monopulse corporate feed waveguide antenna. There are a monopulse circuit and a feed waveguide for each polarized wave. A monopulse circuit has 4 inputs and 4 outputs, which is composed of four magic-Ts. It is used to generate and separate four orthogonal modes for ROM transmission. The radiating part is composed of dual-linear polarized 8x8-slot subarrays. A low-loss and wideband characteristic is achieved by adopting a hollow waveguide and plate laminated diffusion bonding. The design frequency is 61.5GHz, and the band is 57-66GHz.

The authors design the two monopulse circuits, the feed waveguides, and the radiating part, then build up the antenna as shown in **Fig. 1**. 8.5% bandwidth of VSWR less than 2.0 for all of the eight ports is achieved. The isolation between the two input ports is 38 dB or more, and XPD is more than 35 dB.

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Hirokawa Laboratory

Reflection Suppression in the Short-Slot 2-plane Coupler by Step Structure

The conventional short-slot one-plane coupler is used as hybrid or cross coupler in the one-dimensional beam-switching Butler matrix of waveguide structure. If two-dimensional beam-switching is required by conventional Butler matrices, the matrix beam-switching in the horizontal plane and that in that in the vertical plane should be cascaded. The authors have proposed the one-body waveguide short-slot two-plane coupler for key component of the two-dimensional beam-switching Butler matrix.

The bandwidth of the 2-plane coupler is narrower than that of the conventional 1-plane couplers. Because more modes are considered in the coupled region in the 2-plane coupler in comparison with the 1-plane coupler. This paper discusses the reflection suppression of the 2-plane hybrid coupler by introducing a step structure that is analogous for the 1-plane coupler.

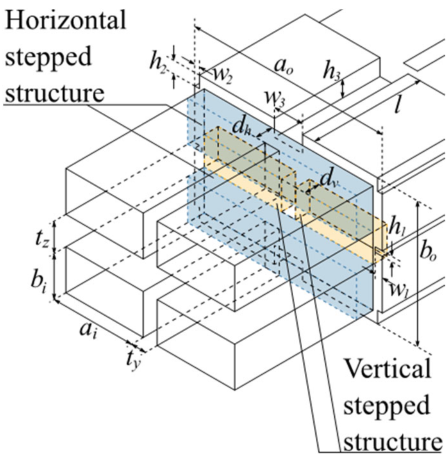

Fig. 1 Step structure in the short-slot 2-plane coupler.

Fig. 1 shows a step structure in the input side of the 2-plane coupler. The step structure has two kinds of stepped regions. One is the horizontal stepped structure as shown in blue in **Fig. 1**, where the top two ports and the bottom two ports, respectively, are connected to one waveguidewith a length of d_h. The other is the vertical stepped structure as shown in orange in **Fig. 1**, where the steps with a length of d_v are removed from the coupled regions. The design frequency is 22 GHz.

In the original 2-plane coupler, the transmissions to the four output-side ports S51-S81 are within −6±0.5 dB at 22.0 GHz. The reflections to the four input-side ports S_{11} and S_{41} are −21 dB, and S_{21} and S_{31} are −25 dB. The stepped structure acts well for the suppression of S_{11} and S_{41} but does not for S_{21} and S_{31}. In the proposed 2-plane coupler, S_{11} and S_{41} are less than −20 dB in 21.3-23.1 GHz, and S_{21} and S_{31} are less than −20 dB in 21.0-23.6 GHz. However, the transmissions to the output-side ports are in a range from −6.9 dB to −5.2 dB.

Reference

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A Semi-rigid Cable Monopole Antenna Inserted into a 60GHz-band Oscillator Chip

Considerable research on antennas integrated into an IC chip is conducted recently for reducing loss. We propose the configuration where an antenna is placed on the thick resin layer of about 200 µm on the opposite side of a CMOS RF circuit. The radiation efficiency is enhanced because of the thick resin layer, and the connecting loss is reduced because of the directly feeding through a hole in the silicon chip. However, the possible processing for an oscillator chip is only drilling. Thus, we propose the configuration inserted a semi-rigid cable monopole antenna into a 60GHz-band oscillator chip.

Fig.1 shows the photographs of fabricated antenna. The outer conductor prevents leakage of an electromagnetic wave into silicon. The inner conductor is connected with a RF pad of the oscillator chip by a gold wire. The oscillator chip is put into a grass-epoxy substrate that has printed wirings for oscillation by DC current.

We measure the radiation power by a random field method using a reverberation chamber and obtain the radiation power of -18.6 dBm. In addition, the output power from the RF pad of the oscillator chip measured by prober is within the range of -12.8 to -11.3 dBm. In analysis, the reflection loss and the material loss are 3.9 dB and 2.3 dB, respectively. The radiation patterns agree well between measurement and simulation and small radiation from the circuit side is confirmed.

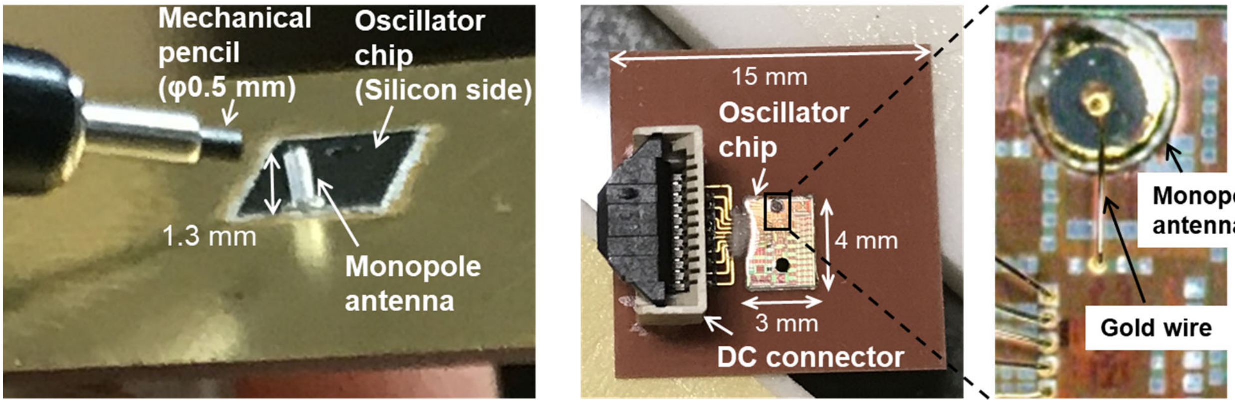

Fig. 1 Photographs of fabricated antenna.

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Okada Laboratory

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

Professor Kenichi Okada

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Assistant Professor Atsushi Shirane

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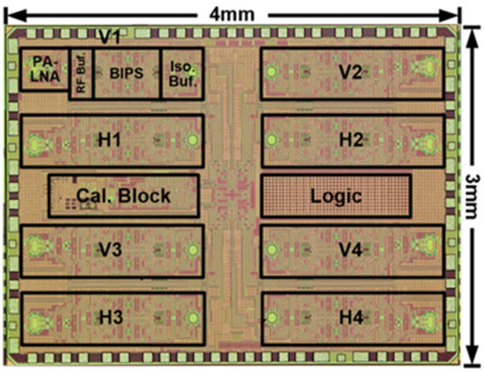
Our Research Interests

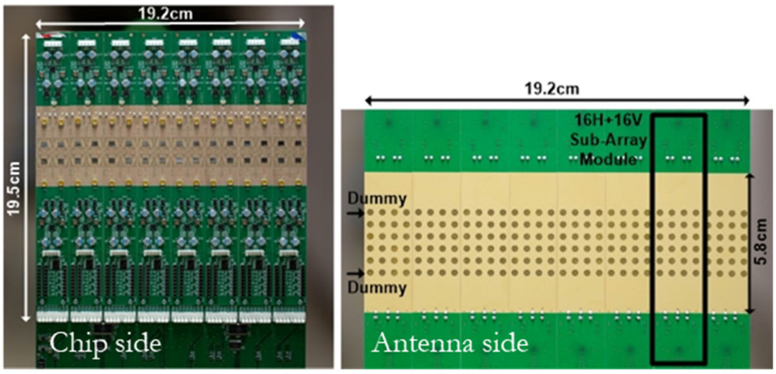
At Okada laboratory, we have been researching RF, analog and digital mixed signal integrated circuit design. Currently, we focus on the following research topics. In this report, we introduce the research highlight of this year about 1) 5G Transceiver, 2) All-Digital-PLL, 3) Atomic Clock.

- 60GHz Millimeter-wave Transceiver
- 5G Phased-array 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

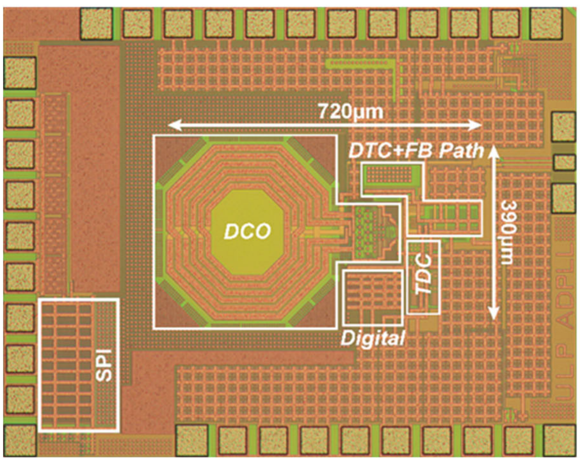


CMOS chip

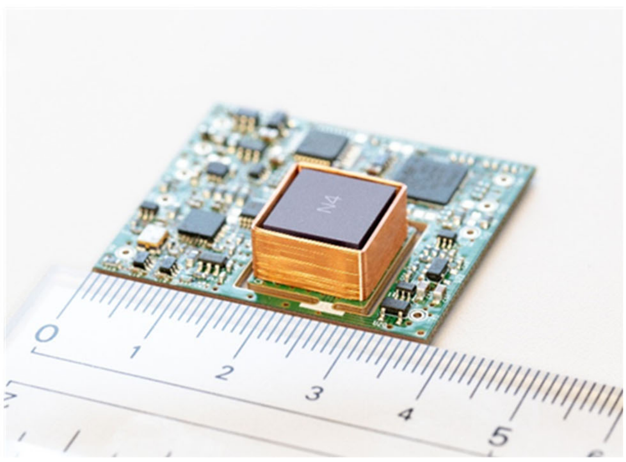


Phased-array module

All-Digital-PLL



Atomic Clock



Okada Laboratory

A 28GHz CMOS Phased-Array Transceiver Supporting Dual-Polarized MIMO for 5G NR

5G NR service will provide extremely-high-speed mobile data access using the millimeter-wave spectrum. For further boosting the data rate and spectrum efficiency, du-al-polarized MIMO (DP-MIMO) will be introduced. Separated phased-arrays will be required for H and V polarizations. However, the increased free-space-path-loss for the 5G NR band n257 (26.5GHz to 29.5GHz) demands numerous elements to cover enough communication distance. Concerning the required considerable number of chips, an area-efficient design will be necessary for a DP-MIMO system targeting 5G NR FR2. **Fig. 1** shows the presented 28-GHz 4H+4V bi-directional transceiver chip supporting DP-MIMO in 65nm CMOS. The proposed neutralized bi-directional amplifier significantly reduces the required on-chip area. A bi-directional vector summing phase shifter is also introduced. The measured RMS phase and gain errors are 0.4° and 0.2dB at 28GHz, respectively. The array module achieves a saturated EIRP of 45.6dBm/pol. at 0° scan when 32H+32V array. In a 1-m OTA measurement, a 4x4 sub-array module supports single-carrier data-rates of 15Gb/s and 6.4Gb/s per polarization in 64QAM and 256QAM, respectively. The measured 400-MHz OFDMA TX-to-RX EVM for the 4x4 sub-array module at 0° scan is -34.4dB in 256QAM. 2x2 DP-MIMO communication with a 400-MHz 5G NR channel bandwidth is also achieved with a 64-QAM EVM of 4.9% for the 4x4 sub-array module.

Fig. 1 shows the system block diagram of the 4H+4V transceiver chip. In consideration of the large-sized phased-array and MIMO configuration in 5G NR, bi-directional technique is utilized in this work for minimizing the on-chip area. The proposed array transceiver is capable of operating in TX and RX modes with the same bi-directional circuit chain. A single-element transceiver consists of 2-stage PA-LNA, RF buffer, phase shifter, and isolation buffer. The 28-GHz signal is distributed by a T-junction

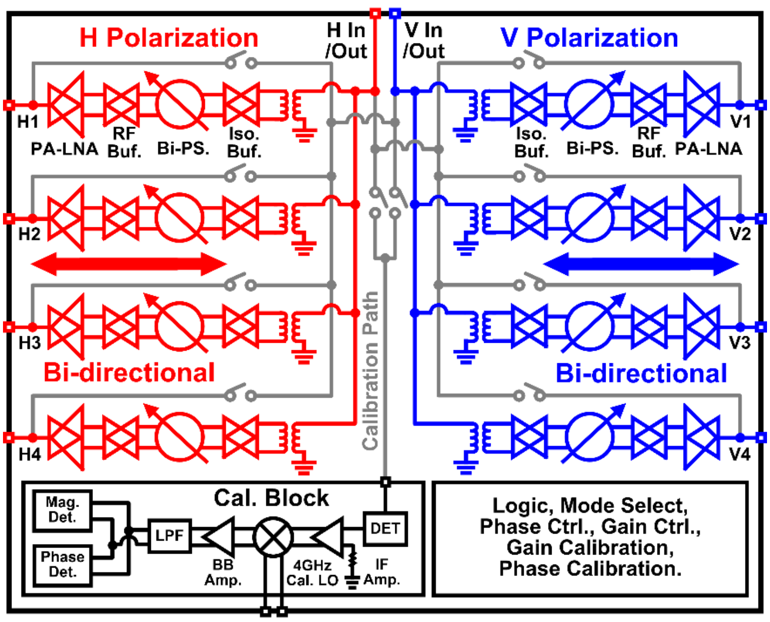


Fig. 1. Block diagram of the proposed 4H+4V 28GHz transceiver chip.

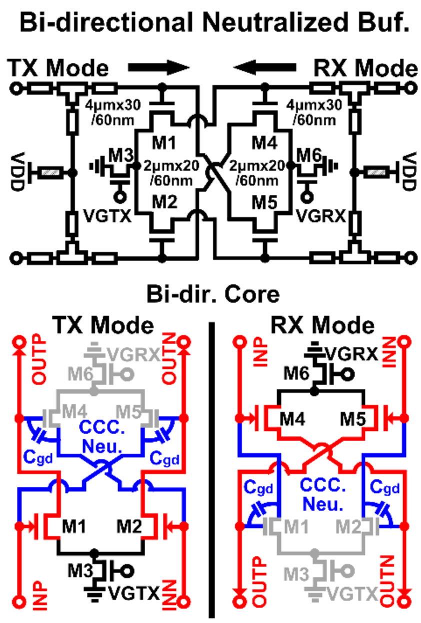


Fig. 2. Proposed neutralized bi-directional core.

divider/combiner to each element in single-ended. After the distribution, an isolation buffer is inserted for suppressing the influence of impedance variation caused by the phase tuning. Thus, independent phase tuning between each element can be realized. For minimizing the magnitude and phase errors between elements, a calibration circuit is integrated into the chip.

The bi-directional amplifiers are designed based on the proposed neutralized bi-directional core as shown in **Fig. 2**. Compared with the conventional switch-based bi-directional approach, the proposed bi-directional amplifier completely shares the inter-stage matching networks between the TX and the RX. Thus, the required on-chip area is further minimized. **Fig. 2** shows the circuit schematic of the proposed neutralized bi-directional core, which consists of two transistor pairs in cross-coupling connection.

Fig. 3 compares this work with the state-of-the-art 28GHz dual-polarized phased-array transceivers. The proposed transceiver chip reports a 2x2 DP-MIMO communication in 64QAM with a significantly reduced area. The proposed chip is fabricated in a standard 65nm CMOS process. The total chip area including pads is 12mm^2. The power consumption is 1.01W/pol. in TX mode and 0.46W/pol. in RX mode.

<table>
<tr><th colspan="2"></th><th colspan="2">This work</th><th>[2] IBM
ISSCC2017</th><th>[1] Qualcomm
ISSCC2018</th><th>[3] UCSD
RFIC 2018</th></tr>
<tr><td colspan="2">Process</td><td colspan="2">65nm CMOS</td><td>0.13μm SiGe</td><td>28nm CMOS</td><td>0.18μm SiGe</td></tr>
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45.6dBm/pol.</td><td>64H+64V
54dBm/pol.</td><td>8H+8V
35dBm/pol.</td><td>4H+4V 26.5dBm/pol.
@P_{1dB}</td></tr>
<tr><td colspan="2">RX NF</td><td colspan="2">4.2dB</td><td>6.0dB</td><td>4.4~4.7dB</td><td>4.8dB</td></tr>
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<tr><td colspan="2">RMS Phase Error</td><td colspan="2">0.4°@28GHz</td><td><1°@28GHz</td><td>N/A</td><td><4°</td></tr>
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4xV-Beamformer</td><td>16xH-TRX,
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IF, LO (w/o PLL)</td><td>24xTRX,
IF, LO</td><td>4xH-Beamformer,
4xV-Beamformer</td></tr>
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@11.3dBm/path
RX:112mW</td><td>TX:319mW
@16.4dBm/path
RX:206mW</td><td>TX:119mW
@11dBm/path
RX:42mW</td><td>TX:220mW
RX:150mW</td></tr>
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<tr><td>64QAM</td><td>256QAM</td><td>64QAM</td></tr>
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64QAM OFDMA</td></tr>
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<tr><td colspan="2">Uplink 64QAM MCS19
400MHz EVM=4.9%**</td></tr>
</table>

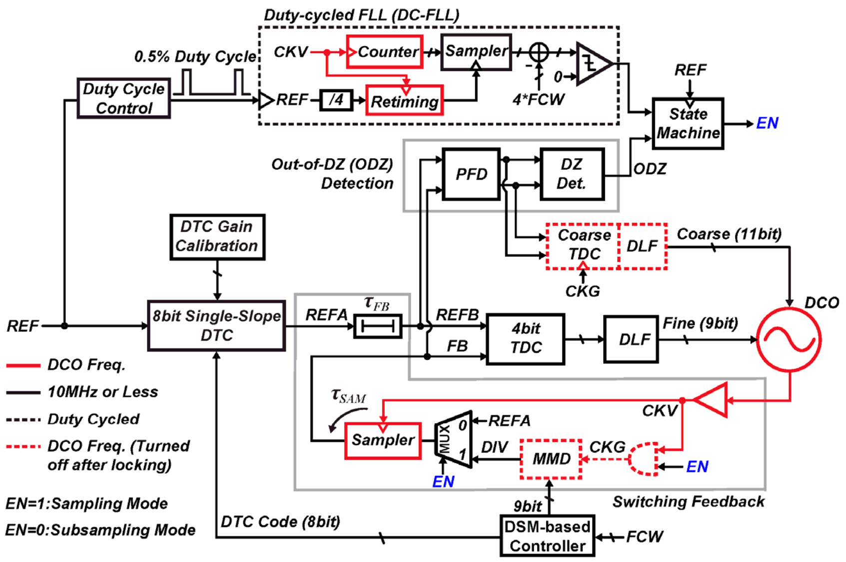
* Estimated from the materials. ** Referred to the RMS magnitude of the constellation.

Fig. 3. Performance comparison of 28GHz phased-array transceivers.

An Ultra-Low Power Fractional-N Digital PLL

The demand for highly energy-efficient circuits and systems has exponentially increased for the use in today's System-on-Chip (SoC). A fractional-N phase-locked loop (PLL) is one of the most important building blocks in SoCs for a variety of applications: the frequency synthesis for wireless transceivers, the system clock generation for processors, memories, and I/O interfaces, etc. Recent developments in fractional-N digital PLLs (DPLLs) have shown great potential for achieving low-power operation and small chip area. However, none of these works have achieved a power consumption of below 500 μW due to the number of building blocks operating at the oscillator frequency. Furthermore, the digitally-controlled oscillator (DCO) in consumed more than 250 μW power for achieving a good phase noise and an enough high amplitude for DPLL locking. Digital subsampling architecture can potentially reduce the overall power consumption by bypassing these high-frequency building blocks. Unfortunately, the absence of the frequency acquisition makes it vulnerable to the sudden or large frequency disturbances. Even though a background frequency-locked loop (FLL) can be applied, it consumes a large power due to the counter working at the DCO frequency. The typical solution to save power consumption is to turn off the FLL after the PLL has been stabilized. Despite the benefit of the power reduction, a subsampling PLL has multiple frequency lock-in ranges near the integer multiple of the reference frequency, which could cause false locking if the frequency disturbances are within those ranges. To address the above issues, this work presents a fractional-N DPLL achieving a record of 265-μW power consumption with a robust phase and frequency acquisition with negligible power overhead in 65nm CMOS technology. It also achieves an RMS jitter of 2.8 ps, which corresponds to an FOM of -236.8 dB.

Fig. 4 shows the overall DPLL architecture. To detect the phase and frequency disturbances, an out-of-deadzone (ODZ) detector and the duty-cycled FLL (DC-FLL) are utilized and operate in the background. Most of the phase and frequency disturbances can be detected by the ODZ detection if the phase error is larger than the DZ, and the state machine will set the EN signal to 1, which switches



w/o and w/ Switching FB

FB Mode	FB Path	DCO	DTC +TDC	Digital*	Total
Samp.[μW]	218	107	45	45	415
Subsamp.[μW]	68	107	45	45	265

*including DC-FLL

w/o and w/ DC-FLL

Duty Cycle	FB Path	DCO	DTC +TDC	Digital	DC-FLL	Total
100%[μW]	68	107	45	42	500	762
5%[μW]	68	107	45	42	3	265

Fig. 4. Proposed fractional-N DPLL with a power consumption of 265μW.

the feedback (FB) path to the sampling PLL mode. After the phase being locked, the state machine produces an EN signal of 0 to switch the FB path to subsampling mode for saving the power from the power-hungry multi-modulus divider (MMD). Thanks to the delay unit after the DTC, the DPLL can remain locked when switching from the sampling mode to the subsampling mode. In the worst case, the frequency of the subsampling PLL may be falsely locked to the integer multiples of the reference frequency while the phase is still locked. Hence, the DZ detector cannot detect any phase errors. A duty-cycled FLL (DC-FLL) is used for assisting the detection of this frequency error and sets EN to 1 to switch the PLL to the sampling mode for relocking. The power consumption can be improved from 415 μW to 265 μW with the proposed switching FB path, which corresponds to a 56% power reduction. A delta-sigma modulator (DSM) based controller is used to generate the delayed sampling clock REFA by using a digital-to-time converter (DTC) for realizing the fractional-N operation. The phase error between CKV and REFB is quantized by a 4-bit TDC. Most of the building blocks are working at 10MHz reference frequency or less. After the phase is locked, only the DCO, the DCO buffer, and the sampler are working at the DCO frequency while the MMD and the coarse TDC are completely turned off. The high-frequency counter inside the DC-FLL is operate with a duty cycle of 0.5%. This limits the power consumption of the FLL to only 3 μW.

The presented fractional-N DPLL occupies an area of 0.28mm^2 in 65nm CMOS. The free-running DCO achieves a phase noise of -107 dBc/Hz at 1MHz frequency offset with a power consumption of 107 μW at 0.45V supply. The rest parts of the DPLL works at 0.85V. The automatic switching FB path consumes a power of 68 μW, which leads to a total power consumption of 265 μW for the whole DPLL. An integrated jitter of 2.8 ps is achieved at the FCW of 246.6. The measured worst-case in-band fractional spur is -52 dBc. **Fig. 5** compares the state-of-art low-power fractional-N PLLs. The presented work breaks 500 μW power record by almost twice with a PLL FOM of -236.8 dB.

	This Work	ISSCC'17 [1]	ISSCC'14 [2]	ISSCC'18 [3]
Technology	65nm	40nm	40nm	65nm
Ref Freq (MHz)	10	N/A	32	52
Out Freq (GHz)	2.20 - 2.80	1.8 - 2.5	2.1 - 2.7	2.0 - 2.8
Power (μW)	**265**	673	860	980
Jitter (ps)	2.8 [10k-40M]	1.98 [10k-10M]	1.71 [1k-100M]	0.53 [10k-10M]
FoM (dB)	**-236.8**	-235.8	-236.0	-245.6
In-Band Frac Spur (dBc)	-52	-56	-38	-56
Power Eff. (μW/GHz)	107	312	358	271
Reference Spur (dBc)	-66	-62	-70	-68
Active Area (mm^2)	0.25	0.18	0.20	0.23

Fig. 5. Comparison table with prior-art fractional-N DPLLs.

Okada Laboratory

Ultra-Low-Power Atomic Clock for Satellite Constellation

Nano/micro satellites in the low earth orbit (LEO), and unmanned-aerial-vehicle base stations (UAV-BS) in the stratosphere are being considered to be used for increasing the coverage and provision of on-demand high data rates of mobile communication networks all over the globe as beyond 5G technology. One of the most important key technologies for such high-speed and long-distance communication is a very accurate time standard, especially for the LEO satellites constellation. Presently, the best time accuracy can be acquired from atomic clocks. Atomic clock assisted GEO satellites such as GPS can be a primary reference, but they suffer from large path loss and delay, degrading the clock accuracy to 10^{-6} in the receiver part. In addition, GPS is not always available in the space, while the conventional atomic clock has deployment difficulties in the large array due to large volume and huge power consumption. For example, due to the special condition of the atomic cell required for reference frequency locking and probing, even a compact atomic clock is still ranging from 150cm^3 to 775cm^3 in size and consumes 1.2W-10W of power. Thus, a miniaturized, low power and low cost time standard is required for each LEO satellite. Recent developments in the photonics and MEMS processes show the potential to realize low power and small volume quantum package of atomic clock based on coherent population trapping (CPT) method. With the reference frequency locking and probing techniques realized by the advanced CMOS integrated circuits, it is now possible to manufacture a small form-factor atomic clock. This work presents a complete ultra-low-power and miniaturized atomic clock (ULPAC) system with the cesium-133 gas cell, vertical-cavity surface-emitting laser (VCSEL), temperature/magnetic controllers inside a quantum package and the driving/controlling circuitry required for complete atomic clock operation. The prototype of ULPAC achieves a long-term Allan deviation of 2.2×10^{-12} at τ=105s while realizing only 15.4cm^3 volume.

Fig. 6 shows the system block diagram of the proposed ULPAC prototype. ULPAC out-puts an accurate 10MHz clock generated by a 10MHz VCXO, which is calibrated by the cesium resonance frequency. 1PPS (1 pulse per second) signal is also generated from the 10MHz clock. The quantum package integrates cesium-133 gas cell, VCSEL, and photo-detector (PD). The D1-line CPT transition of cesium-133 vapor cell exhibits the half of the ground-state hyperfine resonance frequency Δhf/2 of 4.596315885GHz, which is served as a stable reference. By using a fractional-N PLL, the 10MHz clock is multiplied by 459.6315885 times,

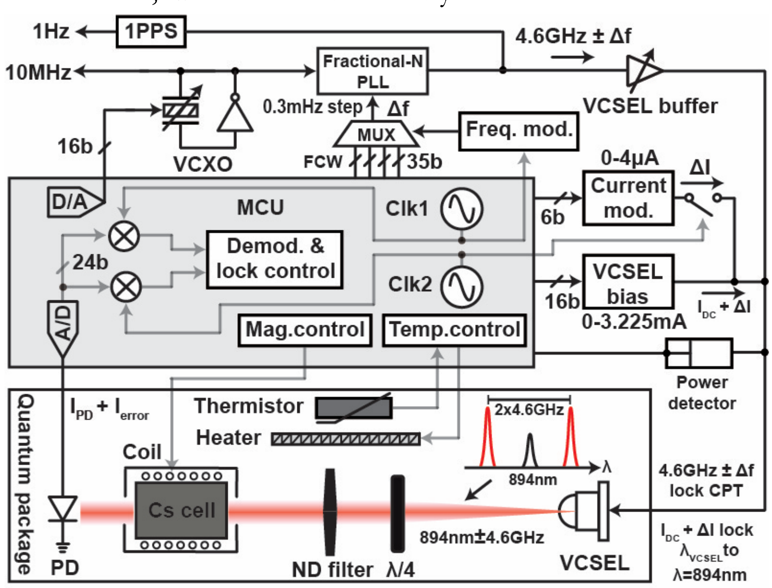


Fig. 6. ULPAC system diagram.

and the multiplied LO signal (f_{LO}) is compared with Δhf/2. The frequency error, Δhf/2 - f_{LO}, is feedbacked to the VCXO control signal for obtaining the very accurate 10MHz clock. The LO signal is fed to the VCSEL after amplification. And the VCSEL produces two first-order sidebands separated by 2×f_{LO} around the VCSEL wavelength (λ_{VCSEL}). The bi-chromatic light from the VCSEL is passed through the λ/4 waveplate and neutral-density (ND) filter. Then it is input to the cesium gas cell. When the λ_{VCSEL} and 2×f_{LO} are exactly matched to the cesium D1 line resonance energy levels, the PD will detect the very sharp and stable peak caused by the CPT. To search the peak, f_{LO} and λ_{VCSEL} are modulated through the PLL (±Δf) and bias current (+ΔI), respectively. The demodulation of this searching and locking loop based on the frequency/current is done by the MCU in this prototype.

Fig. 7 plots a performance comparison about Allan deviation and power consumption, and the prototype of the proposed ULPAC achieves very low power and very stable time accuracy satisfying the satellite communication requirement of 10-11 long-term Allan deviation. **Fig. 8** summaries the key performances of the state-of-the-art atomic/molecular clocks. Thanks to the advanced quantum packaging, the volume of this work is reduced to 15.4cm^3. The frequency synthesizer only consumes 2.0mW including 1PPS generation, while the VCSEL buffer gives 0dBm output at 4.5mW power consumption. The long-term stability is achieved by the well-controlled electromagnetic filed, minimized pressure variation due to temperature variation of gas cell and VCSEL buffer power variation. The power consumption of VCXO, heater, and regulator are 2.9mW, 9.1mW, and 7.9mW, respectively. The total power consumption is 59.9mW.

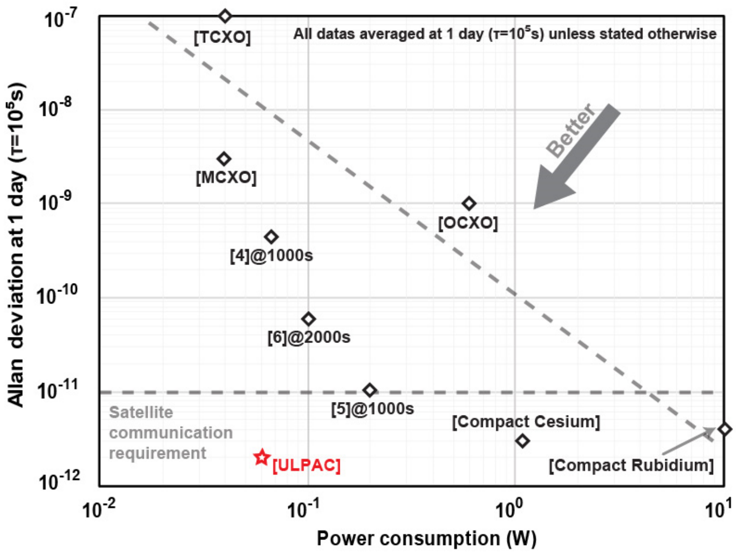


Fig. 7. Long-term stability and power consumption.

Parameter	[3]	[4]	[5]	This work
Integration level &Type	PLL+PA+ Freq. mod. (CSAC)	TX + RX (MC)	PLL+PA+ Freq. mod.+ VCSEL driver (CSAC)	PLL+PA+ Freq. mod.+ VCSEL driver (ULPAC)
Volume [cm^3]	nd	50	16	15
Reference freq. [MHz]	40	80	10	10
Atom & Line	Rb & D1	$^{16}O^{12}C^{32}S$ & N/A	Cs & D1	Cs & D1
PLL output freq. [GHz]	3.4	231.0	4.6	4.6
PLL power cons. [mW]	7.8	66.0	52.0	2.0
VCSEL driver power cons. [mW]	14.7@0dBm	N/A	N/A	4.5mW@0dBm 3.1mW@-5dBm
Allan dev. (τ =10^{0}s) [10^{-11}]	40.0	250.0	30.0	8.4
Allan dev. (τ =10^{5}s) [10^{-11}]	N/A	N/A	N/A	0.22

Fig. 8. Performance comparison table.

Fukawa Laboratory

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received the B.S. and M.S. degrees in physics, and the Dr. Eng. degree in electrical and electronics engineering, all from Tokyo Institute of Technology, Tokyo, Japan, in 1985, 1987, and 1998 respectively. He joined Nippon Telegraph and Telephone Corporation (NTT), Japan, in 1987. Since then, he has been engaged in research on digital mobile radio communication systems and applications of the adaptive signal processing, including adaptive equalization, interference cancellation, and adaptive arrays. He was a Senior Research Engineer at NTT Mobile Communications Network Inc. (NTT DoCoMo), from 1994 to 2000, and an Associate Professor at the Tokyo Institute of Technology, from 2000 to 2014. Since 2014 March, he has been a Professor at the Tokyo Institute of Technology. Prof. Fukawa is a 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, 10 Gbps 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 10 Gbps

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.

Parameter Control Method for Massive MIMO using Hybrid Beamforming [9], [24], [27]

For 5G mobile communication system, massive MIMO uses over 100 antenna elements on the station side, and is considered one of the most promising schemes. However, full digital beamforming (DB) for massive MIMO requires as many baseband (BB) and radio frequency (RF) chains as antenna elements, which costs a lot of money and consumes high energy. To solve this issue, hybrid beamforming (HB) is introduced. Since HB consists of digital beamforming (DB) and analog beamforming (AB) that can be implemented by phase shifters, HB can reduce the number of BB and RF chains drastically. Despite such an advantage, station utilizing HB-MIMO cannot estimate channel impulse responses accurately and thus cannot control precoding matrix efficiently. We propose a joint estimation scheme of both the phases of phases shifters in AB and the precoding matrix used in DB.

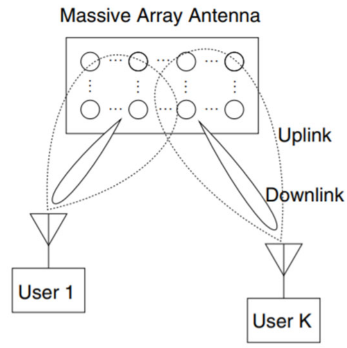


Fig. 1. The concept of multiuser massive MIMO.

In this research, multiuser MIMO is considered as illustrated in **Fig. 1**. Base station supports K user terminals with an array antenna consisting of more than 100 elements. Each of the K user terminals has only 1 TX/RX antenna, and the user terminals share same frequency channel simultaneously. Moreover, TDD (Time Division Duplex) is applied in the situation, namely uplink and downlink transmission are done in the same spectrum. Therefore, the channel impulse response estimated in uplink can be used for controlling downlink precoding matrix with the reciprocity of channel. Although time-invariant frequency selective fading channel is assumed as the channel model, for an OFDM subcarrier signal, the channel will be equivalent to flat fading.

The structure of HB is illustrated in **Fig. 2** The proposed estimation scheme consists of the following seven steps: i) Firstly, the channel matrix for full DB is estimated using the received training signals in uplink. ii) Next, an MMSE precoding matrix is obtained from the estimated full DB channel matrix. iii) A difference matrix between the MMSE precoding matrix and the precoding matrix of AB multiplied by that of DB for the HB is calculated. The cost function is defined as the squared Frobenius norm of the difference matrix. iv) Hold the phases in AB (with phase 0 in the first iteration, and with the obtained phases obtained in the previous iteration in the other iteration), and minimize the cost function with respect to the precoding matrix of DB to obtain the precoding matrix of DB. v) Hold the precoding matrix of DB with the precoding matrix obtained in the previous step, and minimize the cost function with respect to the phases in AB. vi) Steps iv) and v) are repeated. vii) After the iteration stops, the

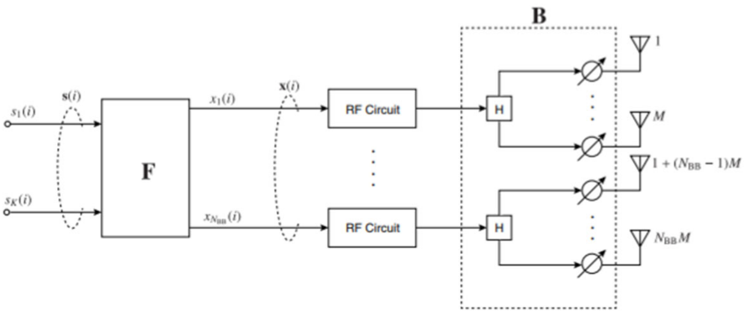


Fig. 2. The structure of hybrid beamforming (transmitter).

optimum phases are quantized. Multiplying the above-mentioned full DB channel matrix by the precoding matrix of AB with the discrete-value phases yields an equivalent channel matrix. Based on the equivalent channel matrix, the MMSE precoding matrix can be obtained and used as the precoding matrix of DB.

We compare the performance of proposed HB method and full DB by computer simulation. The estimation of the channel matrix for full DB is assumed to be ideal in the simulation. **Fig. 3** shows the average bit error rate (BER) performance with 6 different angular spreads. It can be known from the results that the average BER gets better performance with higher angular spread, which may result from increasing spatial diversity. **Fig. 4** shows the downlink average BER performance of full DB and HB. The BER performance of the proposed HB is much worse than that of full DB at high SNR regimes, whereas the proposed HB can achieve a comparable BER performance to that of full DB at low SNR regimes.

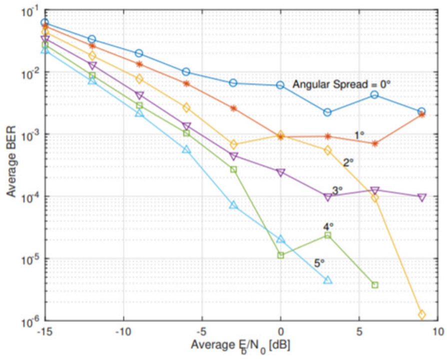


Fig. 3. BER performance with 6 different angular spread.

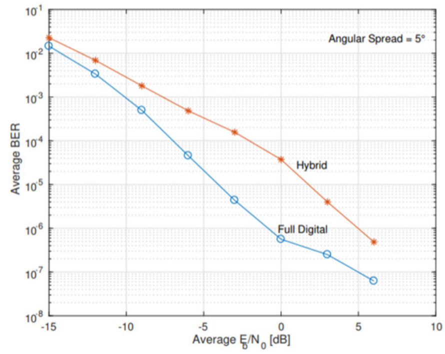


Fig. 4. BER performance of HB and full DB.

Transmit Power and Beamforming Control Using Neural Networks for MIMO Small Cell Networks with Interference Cancellation [10], [13]

High density cellular network is one solution to support the growing data traffic. In a densely deployed cellular topology, a relatively small area contains many small cells that are served by each small, inexpensive, and low-power base station. Although the dense deployment of the base stations brings a higher potential of system capacity, it causes the coverage areas of neighboring small cells to overlap. This overlapping phenomena increases inter-cell interference and degrades the system capacity. To tackle this problem, we propose a neural network (NN) based inter-cell interference coordination (ICIC) scheme. The proposed scheme consists of both an interference cancellation (IC) technique on the receiver side, and a power/beamforming control on the transmitter side. The receiver removes interfering signals with high received power by IC, whereas the transmitter searches for a combination that maximizes the system capacity from a predetermined set of precoding matrices and transmit power levels. The searching process could be accomplished by applying a greedy search that goes through every possible combination. However, the greedy search requires huge computational complexity. To reduce the computational complexity, we apply NN to calculation of a power/beamforming configuration. The training process of NN consists of two steps. The first step is an unsupervised pre-training based on restricted Boltzmann machine (RBM). This step extracts features from the fed channel data and speeds up the entire training process. The second step is a supervised training succeeding the pre-training process. After the entire training process, the NN can output power/beamforming configuration given channels of neighboring small cells as input. Simulation results show that the proposed ICIC scheme can obtain nearly optimal system capacity compared with greedy search.

Consider a time division duplexing (TDD) MIMO system of K links shown by **Fig. 5**. Channel capacity of the i-th link can be written as

$$C_i = \log_2 \det[\mathbf{I}_N + \frac{P_i}{N}\widetilde{\boldsymbol{R}}_{\mathrm{NI},i}^{-1}\mathbf{G}_{i,i}\mathbf{F}_i(\mathbf{G}_{i,i}\mathbf{F}_i)^H],$$

and

$$\widetilde{\boldsymbol{R}}_{\mathrm{NI},i} = \sum_{k\neq i, k\notin \psi_i}\frac{P_k}{N}\mathbf{G}_{i,k}(\mathbf{G}_{i,k}\mathbf{F}_k)^H + \sigma_n^2\mathbf{I}_N,$$

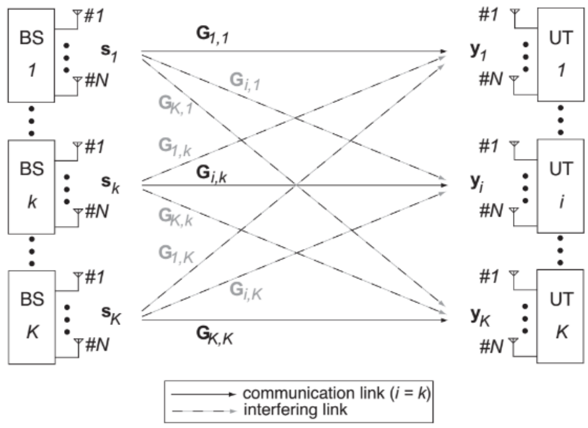


Fig. 5. TDD MIMO small cells network with K links.

where $\mathbf{G}_{i,k}$ is the channel between the i-th UT and the k-th BS, $\mathbf{F}_k$ and P_k are the precoding matrix and transmitting power of the k-th BS, The system capacity is defined by $C = \frac{1}{K}\sum_{k=1}^{K} C_k$. It can be seen that C is a function of $\mathbf{F}_k$ and P_k given $\mathbf{G}_{i,k}$ and σ_n^2. It is difficult to maximize C on continuous $\mathbf{F}_k$ and P_k, a possible solution to this optimization problem is to maximize C on discrete $\mathbf{F}_k$ and P_k. Define a set $\chi = \{\widetilde{\mathbf{P}}_1, \dots, \widetilde{\mathbf{P}}_{|\chi|}\}$ and $\omega = \{\widetilde{\mathbf{F}}_1, \dots, \widetilde{\mathbf{F}}_{|\omega|}\}$ contains all possible discrete $\mathbf{F}_k$ and P_k respectively. The optimization problem can be written as $(\hat{P}_i, \hat{\mathbf{F}}_k) = \arg \max_{\substack{\hat{P}_i\in\omega, \hat{\mathbf{F}}_k\in\chi \\ for\ all\ i,k}} (C)$.

Fig. 6 shows the NN based system which outputs $\mathbf{F}_k$ and P_k combination. The input vector of this NN is constructed as

$$u_{0,b} = \begin{cases} \beta\left[\|\widehat{\mathbf{G}}_{i,k}\|_F^2\right] \\ \beta\left[\|\widehat{\mathbf{G}}_{i,k}\{\widetilde{\mathbf{F}}_{|1,\dots,\omega|}\}\|_F^2\right] \end{cases},$$

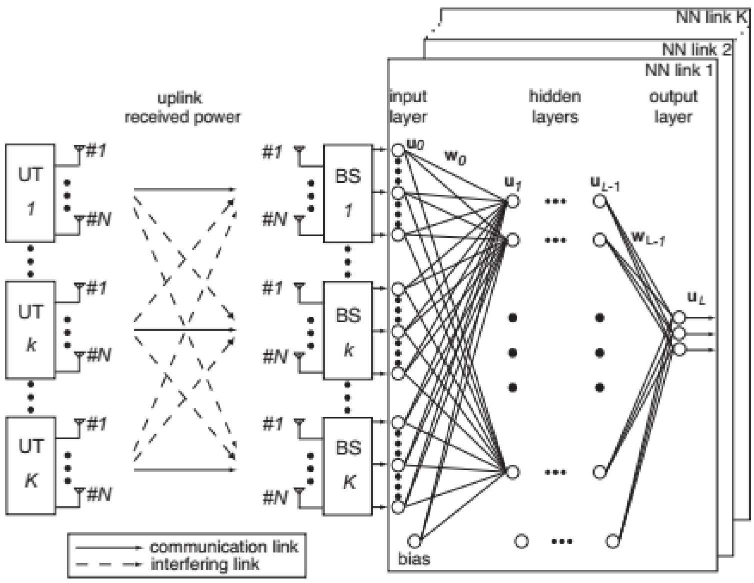


Fig. 6. BF and transmitting power control system based on NN.

where $\widehat{\mathbf{G}}_{i,k}$ is channel estimation and β is a normalization constant. The first construction of input vector only reserves the power of the channel but loses phase information. This input construction is used to only output P_k. With the second construction of input vector, the NN can output a combination of $\mathbf{F}_k$ and P_k. Each node in the input and hidden layers of the NN uses sigmoid function as activation function. The output layer uses softmax function as activation function. The labels of the training sample are generated with greedy search and in a one-hot coded format. The cost function is constructed by a sum of a cross-entropy loss term and an L2 regularization term regularizing all the weight parameters in the NN. Gradient descent is used in backpropagation to minimize the cost function.

To speed up the training process, a RBM based unsupervised pre-training process is performed before the previously mentioned supervised training process. This pre-training process can extract features fed with $\hat{\mathbf{G}}_{i,k}$ only and without any labels. Contrastive Divergence-1 is used in the pre-training process to update parameters. An L2 regularization term of all weight parameters is subtracted from the maximizing function.

Fig. 7 shows the CDF of system capacity with NNs trained by different learning rates u and greedy search serves as a base line. It can be seen that with a learning rate of $u = 0.001$, the highest system capacity is obtained. **Fig. 8** shows the CDF of system capacity $M = 1$ means that the interference of the highest power is canceled by IC, and $M = 0$ means that no IC is operated. It can be seen that, when $M = 0$, and only P_k is controlled, the proposed scheme achieve 99% system capacity at CDF = 0.5 compared with greedy search. If P_k and $\mathbf{F}_k$ are controlled, the proposed scheme achieved 90% system capacity at CDF = 0.5 compared with greedy search. When $M = 1$, system capacity at CDF = 0.5 is doubled compare with the system capacity when $M = 0$.

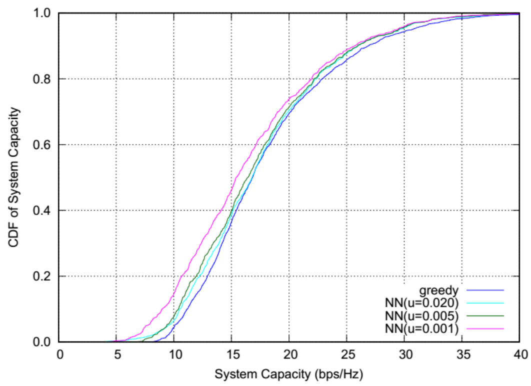


Fig. 7. CDF of system capacity of NNs trained with different u.

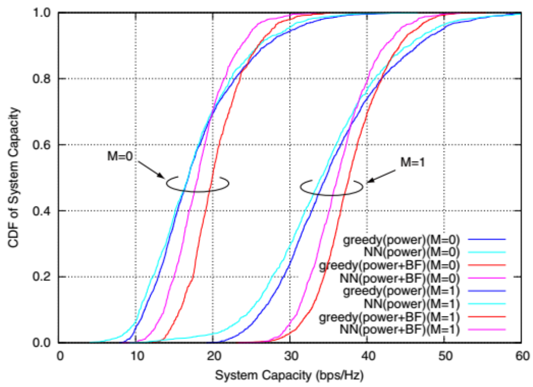


Fig. 8. CDF of system capacities.

Phase Rotated Non-Orthogonal Multiple Access [6], [8], [17], [19]

As a multiple access technique candidate of the next generation wireless communications (5G), non-orthogonal multiple access (NOMA) has attracted much attention because it can improve the spectral efficiency more significantly than conventional orthogonal multiple access (OMA) techniques. In the downlink system, NOMA assigns transmit (Tx) power levels to plural users under the total power constraint, and superposes the Tx signals for the users. On the receiver side, successive interference cancellation (SIC) subtracts dominant interfering signals from received signals and detects the desired signals. Power allocation methods for NOMA have been proposed to optimize/sub-optimize the system performance or to minimize the total Tx power, while considering the user pairing/selection and fairness for the uplink or downlink systems. When a Tx power level of one user is roughly equal to those of the other users, however, bit error rate (BER) performance of the above-mentioned power allocation methods is deteriorated. In such a case, the BER performance of not only lower power but also higher power users severely degrade owing to the error propagation of SIC. To improve such BER performance, the maximum likelihood detection (MLD) has been applied to NOMA. The MLD, which can be considered a kind of multiuser detection (MUD), processes the superposed signal for the users and thus is free from the error propagation. The improvement is remarkable in some situations, while the performance severely degrades when some of the superposed constellation points are close to or overlap each other.

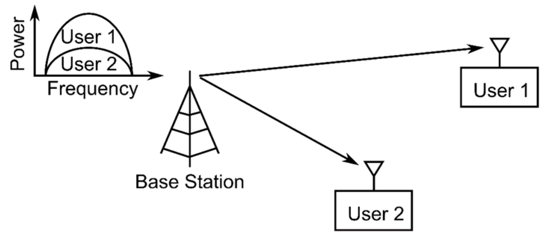


Fig. 9. A system model of 2-user downlink NOMA.

To cope with the above problem, this research proposes a novel NOMA scheme that employs phase rotation and joint MUD and SIC. The phase of the complex modulation symbol for the high signal-to-noise ratio (SNR) user is rotated and then the phase rotated symbol is combined with the symbol for the low SNR user, which can increase the minimum distance between the superposed constellation points. Although the phase rotation has already been proposed in some previous literatures, where the scheme is evaluated in the uplink only, and optimization for the angle of phase rotation is not necessary. Conversely, this research applies the phase rotation to the downlink NOMA systems and optimizes the angle of the phase rotation in the case of two modulation schemes. On the receiver side, the joint MUD and SIC calculates log likelihood ratios (LLRs) of coded bits on the basis of MLD and then provides LLRs of the low SNR user to the corresponding channel decoder. The replica signals of the low SNR user are generated from the decoded bits and then are subtracted from the received signals in order to calculate LLRs of the high SNR user more accurately. The joint MUD and SIC can compensate for the BER degradation, from which the MUD suffers when the minimum distance between the superposed constellation points is maximized but very short.

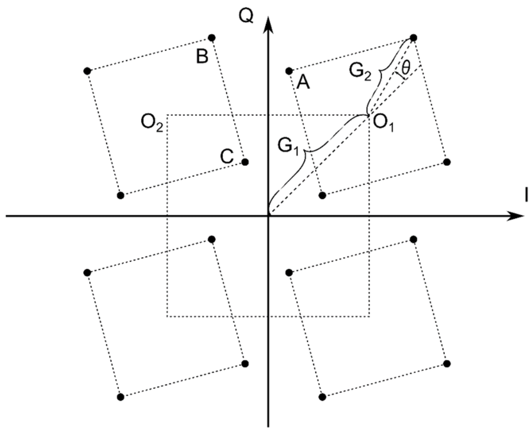


Fig. 10. Superposed constellation points of (QPSK, QPSK) case.

For simplicity, this report considers only 2-user downlink NOMA. **Fig. 9** shows the considered system model, in which the base station (BS) with a single Tx antenna simultaneously transmits signals to the two users over the same channel. Let us assume single carrier transmission with the non-Gray-mapped composite. It is also assumed that the two users have only a single receive (Rx) antenna. The BS assigns higher and lower Tx power levels to the lower and higher SNR users, i.e., user 1 and user 2, respectively. **Fig. 10** illustrates a constellation example of the proposed scheme, where the modulation schemes of the users are both QPSK, and θ is the angle of the phase rotation for the complex modulation symbol of user 2. The proposed scheme modifies the Tx signal into $x = G_1 x_1 + G_2 \exp(j\theta)\, x_2$, where x_i, $i = 1, 2$, is the complex modulation symbol of the i-th user, and is the amplitude gain for x_i. The optimized phase can increase the minimum distance between the superposed constellation points, which can drastically improve the BER performance of NOMA even when the assigned Tx power levels of the users are almost the same.

Fig. 11 shows a block diagram of a receiver with the standard MUD for the users. The MUD in **Fig. 11** calculates the log likelihood function of the users, $\alpha_i(s)$, as

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

where $s \in \mathcal{S}(\theta)$, and $\mathcal{S}(\theta)$ is the set of candidates for the Tx signal x, which is redefined previously, and is a function of θ. Using the log likelihood function, the LLR of a coded bit $b_a^{(k)}$ for the i-th user's receiver, $\lambda_i\left(b_a^{(k)}\right)$, is obtained as

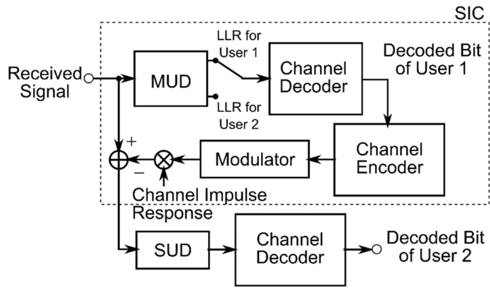


Fig. 11. A block diagram of joint MUD and SIC for user 2.

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

where $b_a^{(k)}$ (k = 1, 2) 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. Note that this scheme is not optimal because MUD with the channel decoding is not optimized.

When the minimum distance between the superposed constellation points is maximized but 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 user 2 as interference, the MUD can improve the BER performance of user 1 compared to the SUD. The 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.

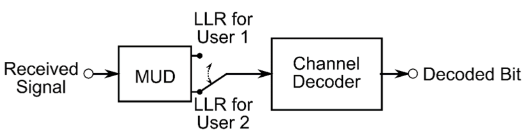


Fig. 12. A block diagram of a receiver with the standard MUD for the users.

In **Figs. 13** and **14**, which are examples of (QPSK, QPSK), it can be seen that the proposed phase rotated NOMA using MUD can achieve the best (average) BER performance for user 1, while that using joint MUD and SIC can achieve the best BER performance for user 2.

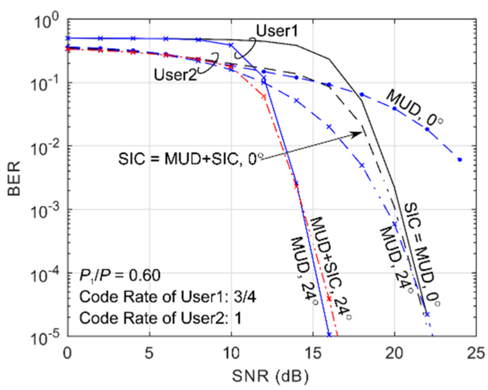


Fig. 13. BER over AWGN channel.

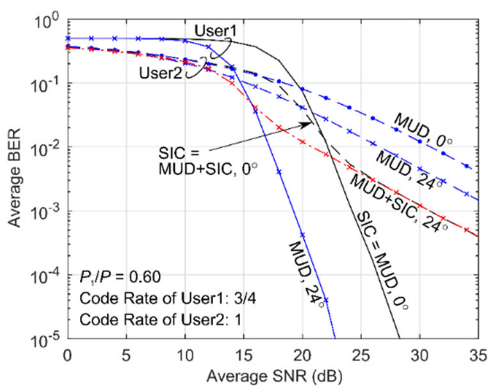


Fig. 14. Average BER over i.i.d. Rayleigh fading channel.

Aoyagi Laboratory

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

Associate Professor Takahiro Aoyagi

Associate Professor Takahiro Aoyagi was born in Yokohama, Japan, on November 1970. He received B. Eng., M.Eng., and D.Eng. degrees from Tokyo Institute of Technology, Tokyo, Japan, in 1993, 1995, 1998, respectively. He has been an Associate Professor of the Department of Electrical and Electronic Engineering, School of Engineering, Tokyo Institute of Technology. His field of research is electromagnetic compatibility, wave propagation, communication systems, and electromagnetic wave engineering. He has received the young scientist award of the 27th symposium on ultrasonic electronics, 2007. Dr. Aoyagi is a member of IEEE, the Acoustical Society of Japan, the Japan Society of Applied Physics, and the Institute of Electronics, Information and Communication Engineers.

Recent Research Topics

- Electromagnetic Compatibility
  - Electromagnetic Wave Absorber Analysis and Design
  - Development of Source Estimation Method for EMC
  - Analysis and Design Method for Reverberation Chambers
- Wave Propagation
  - Wave Propagation in Wireless Body Area Networks (WBANs)
    - Dynamic Channel Modeling for WBANs
    - Antenna De-embedding for WBANs
  - Measurement and Wave Propagation of In-Body
    - Measurement of Abdominal Fat by Microwave
- Communication Systems
  - Tera Hertz Telecommunication Systems for WBANs
  - Human Motion Classification and Energy Efficient Design by Radio

Modeling of Shadowing States of On-Off Body Propagation of Wireless Body Area Network During Human Walking using Simple Geometrical Calculation

In body area networks, wave propagation channel fluctuates by shadowing caused by human movement. In this research, on-off body propagation of body area network during human walking for seven on-body antennas and an external access point is geometrically modeled by plane wave incident direction parameters; zenith and azimuth. By shadowing state estimation using ray tracing technique, LOS/NLOS state is calculated for each zenith and azimuth parameters. The LOS/NLOS boundary of shadowing state for individual time frame and receiving position is approximated by two boundary lines with four parameters. As a result, time variation of the on-off body shadowing parameters of human walking between the receiving position on right hand and the external access point is shown. To investigate other human movements and exhibit derived parameters are left for further research.

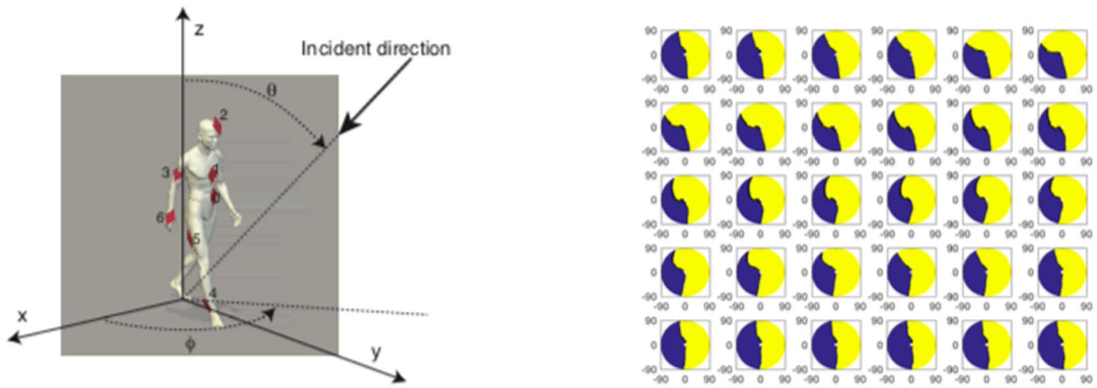


Fig 1. (Left) Geometry of on-off WBAN, (Right) Temporal Variation of Shadowing State of on-off WBAN propagation with respect to azimuth and altitude.

Consideration of Antenna Directions for High Frequency Wireless Body Area Networks During Human Walking Movement

Considering increased requirements for high speed and capacity in wireless communications, frequency bands become higher, e.g. millimeter wave or terahertz wave. In these high frequency bands, beamforming or beam steering is employed to gain stable connectivity. On-body body area network is one of fascinate application of these high capacity frequency bands. However, directions of on-body antennas largely vary and shadowing frequently occurs due to human movements. In this research, variation of antenna directions and shadowing of on-body propagation during human walk movement is investigated. As a result, range of antenna rotation and shadowing rate, which can be used future system design of high frequency body area networks, is clarified.

Nishikata Laboratory

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

Associate Professor Atsuhiro Nishikata

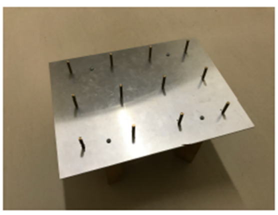
Assoc. Prof. Atsuhiro Nishikata was born in 1961, Tokyo, Japan. He received his B.S. degree in physics, M.E. and D.E. degrees in electrical and electronic engineering, all from Tokyo Institute of Technology in 1984, 1986 and 1989, respectively. From 1989 to 1993, he was a Researcher at Electromagnetic Compatibility Research Group in Communications Research Laboratory; CRL (predecessor of National Institute of Information and Communications Technology; 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

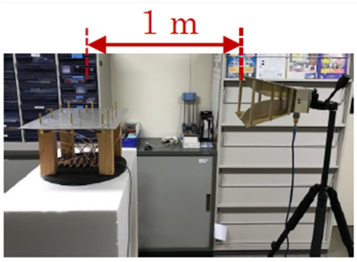
- **Communication Experiment at 2.4 GHz by ASK-modulated Retroreflector**
- **Detection Experiment at 2.4 GHz by M-sequence-modulated Retroreflector**
- **Impulsive Magnetic Source Localization by Two Loop Antennas and a Turntable**
- **Analysis for Induced Noise on Communication Line by MAGLEV Train**
- **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)

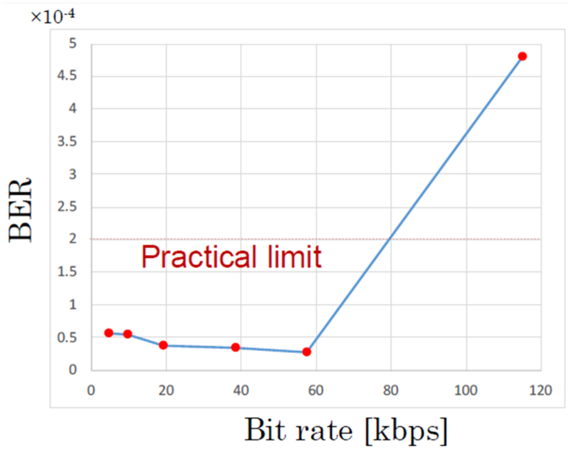
Retroreflecting communication is proposed as a possible means of radio resource saving. Here, communication is realized by modulated retroreflection of incoming wave, without RF transmitter or active beam-forming architecture on the reflector side. In this experiment, 3×4 Van Atta array retroreflector was combined with GaAs switch array modulator that shunts each transmission line at its center. Then, it was irradiated with 2.41 GHz CW from the reader side's horn antenna, and the retroreflected wave was received by the same antenna and demodulated with homodyne detection. Plain text



4×3 Van Atta array



Experiment

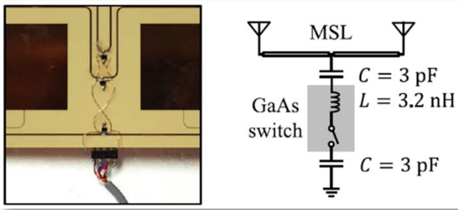


was converted to serial signal and was used to drive the GaAs switch. The retroreflected signal was successfully decoded and confirmed on a PC screen. BER characteristics was measured with changing the bit rate from 4.8 to 115.2 kbps. As a result, practical BER $(< 2 \times 10^{-4})$ was obtained up to the bit rate of 57.6 kbps.

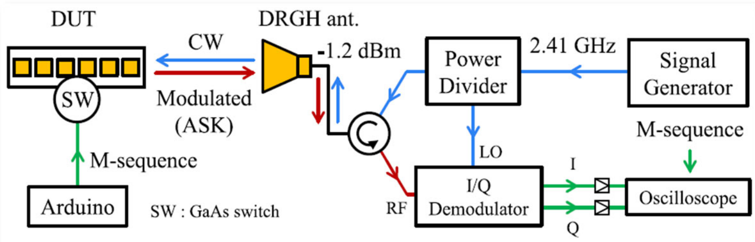
An Experiment of Reflected Wave Detection by Using Thin Six-element Retroreflector with ASK Modulation by Maximum Length Sequence (A collaborative work with NICT)

Retroreflectivity appears by arranging multiple antennas and connecting each pair. This structure, known as Van Atta array, can realize high Radar-Cross-Section reflector. Possible application of the retroreflector may be a safety tag that is easily detected by the anti-collision radar on vehicles, or by the search party's radar. To enhance the detectability, we manufactured a switched retroreflector on printed-circuit-board. Retroreflected wave that was ASK modulated with M-sequence was received by DRGH antenna, then IQ demodulated and recorded. Recorded signal was cross-correlated with original M-sequence signal to yield periodic pulses. Averaged pulse was detected if it was prominent from the background noise. In the experiment at the building corridor, the distance characteristics up to 24 m distance was measured. Target retroreflector was successfully detected in all distances except at nulls due to multipath interference.

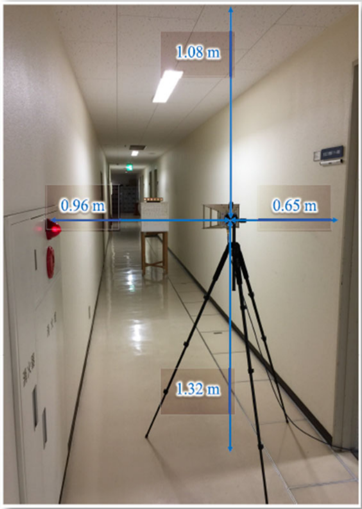
PCB-type 6-element retroreflector



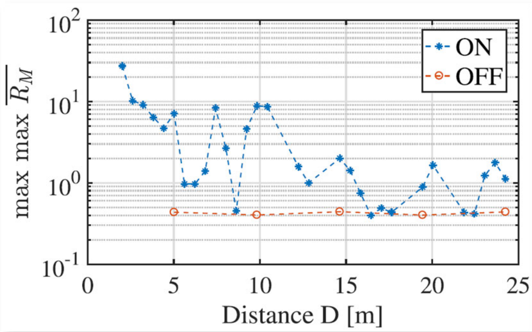
GaAs switches shunting the MSL



Block diagram of the experiment

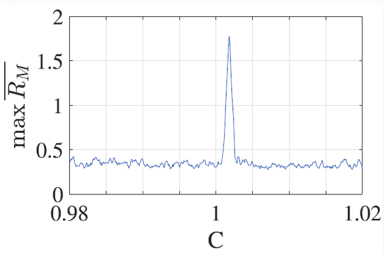


Experiment at the corridor



Detected signal level vs distance (red:BGN)

A M-sequence has insufficient code varieties. It requires to enhance the variety for target identification purpose. Since the symbol rates of M-sequence (of retroreflector side and of reader side) are independent, the latter was fine-tuned by the multiplier C. Resulting "tuning curve" with respect to C implied that the same M-sequence having different symbol rate more than 0.5 % are regarded as "different" code.



Tuning curve by symbol rate

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.

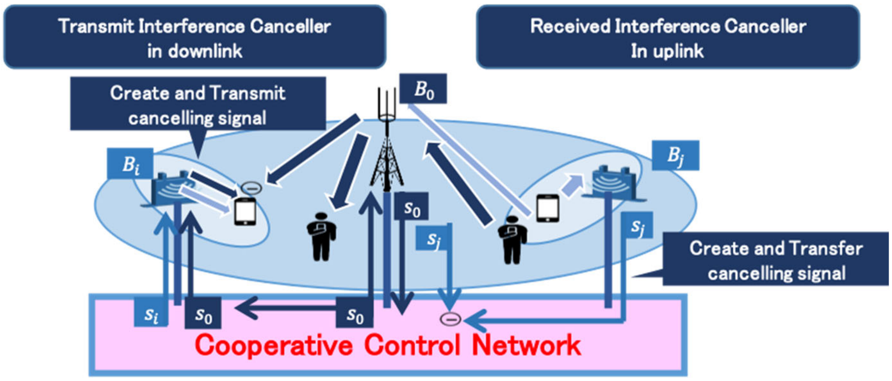
Recent Research Topics

- **3D Layered Cell Construction in Broadband Mobile Communication**
  - Transmit and Receive Interference Canceller for 3D Layered Cell Construction in Broadband Mobile Communication
  - Path loss model for 3D Layered Cell Construction in Broadband Mobile Communication

A Study on Transmit and Receive Interference Canceller for 3D Layered Cell Construction in Broadband Mobile Communication [1][4][6][7]

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" 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.

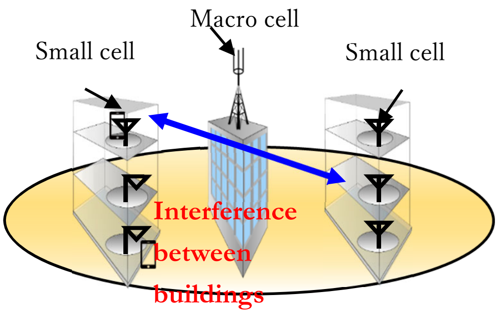
By using these proposed interference cancellers, we showed that the communication quality such as SINR (Signal power to Noise and Interference power Ratio) and communication capacity in small cells can be improved remarkably.

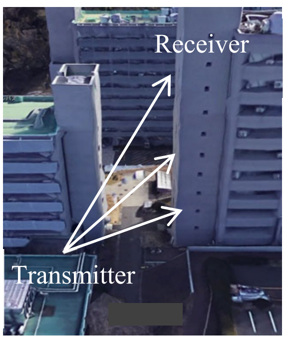


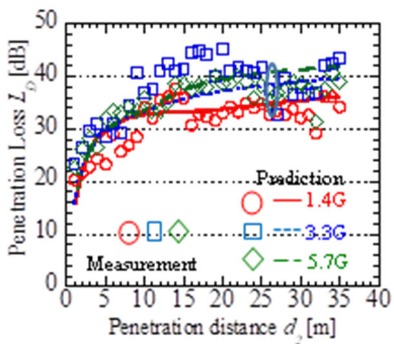
A Study on Path loss model for 3D Layered Cell Construction in Broadband Mobile Communication[2][3][5]

In order to overcome the increasing traffic problems of mobile terminal for use in high-rise floors of buildings, the three-dimensional (3D) layered cell construction which has the small cells in various floors is considered. To evaluate the wireless transmission technology for the 3D layered cell construction, it is necessary to clarify the time-spatial characteristics composed of the path loss, the delay profile and the spatial arrival angular profile for travelling waves from indoor high-rise office to another indoor high-rise office.

In this research, we measured the path loss characteristic as one of the time-spatial characteristics, and developed the path loss model based on measured data. The developed model is versatile, and we will propose this model to ITU-R (International Telecommunication Union Radiocommunication sector) as a global standard model.







Okumura Laboratory

Visiting Professor Yukihiko Okumura

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

Research Interests

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

Okumura laboratory focuses on the flowing research topics:

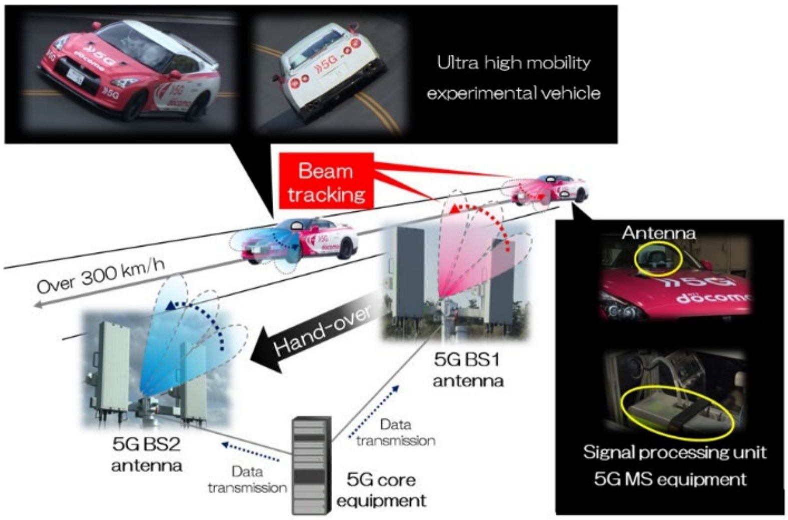
- ✓ ***Proposal and performance evaluation of radio access system for next-generation mobile communication system***
- ✓ ***Radio access technologies for further enhancement of next-generation mobile communication system***
- ✓ ***Radio control technologies and mobile services and applications for further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

In addition to computer simulations etc. on above research topics, experimental trials using experimental equipment are promoted, and students can tackle a variety of researches in the state-of-the-art corporate research and development environment.

Recent Research Topics

5G Transmission Experiment with Ultra High Mobility

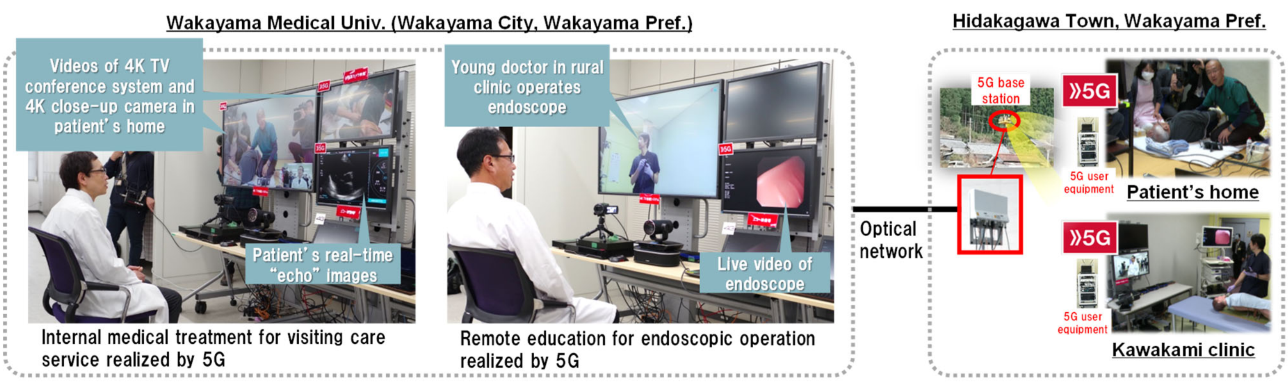
In order to support ultra-high mobility on a bullet train, in April 2018, we conducted an outdoor experimental trial using the specially customized vehicle with the velocity of up to 300 km/h. This figure shows appearances of the base station (BS) and the mobile station (MS) of the 5G prototypes, respectively. The experimental trial employs two BS antennas with Massive MIMO and performs hand-over experiment between two BSs.



We were world-first successful of following four experiments to verify possibility of receiving 5G service in super high-speed mobile environments: (1) 5G data transmission in maximum speed of 305 km/h, (2) downlink 5G transmission achieves 1.1 Gbps throughput in ultra-high speed of 293 km/h, (3) hand-over between two BSs under 290 km/h condition, (4) uplink 5G transmission of 4K high frame-rate live stream from vehicle under 200 km/h.

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

We conducted 5G system trials of an advanced remote medical examination for (1) internal medical treatment for visiting care service, (2) remote education for endoscopic operation, providing improved medical examinations in rural and mountainous areas, comparable to those available in urban general hospitals in this figure.



We connected the Wakayama Medical University and the Kawakami Clinic/patient's home in Hidakagawa Town of Wakayama Prefecture by network including 5G. We then verified capabilities to transmit video from a 4K high-definition close-up camera, and from other equipment used for internal examinations, such as ultrasonic imaging (echo-grams) and endoscope, and also a 4K high-definition video conferencing system for medical interviews and consultations between doctors.

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Takada Laboratory

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[6] Yu Tao, Azril Haniz, Kentaro Sano, Ryosuke Iwata, Ryouta Kosaka, Yusuke Kuki, Gia Khanh Tran, Jun-ichi Takada, Kei Sakaguchi, "A Guide of Fingerprint Based Radio Emitter Localization Using Multiple Sensors (invited)," IEICE Transactions on Communications, vol. E101-B, no. 10, pp. 2104-2119, Oct. 2018.
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[10] Tossaporn Srisooksai, Kamol Kaemarungsi, Jun-ichi Takada, and Kentaro Saito, "Radio Propagation Measurement and Characterization in Outdoor Tall Food Grass Agriculture Field for Wireless Sensor Network at 2.4 GHz Band," Progress In Electromagnetics Research C, Vol. 88, 43-58, 2018.
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[12] Nopphon Keerativoranan, Azril Haniz, Kentaro Saito, and Jun-ichi Takada, "Mitigation of CSI Temporal Phase Rotation with B2B Calibration Method for Fine-Grained Motion Detection Analysis on Commodity Wi-Fi Devices," Sensors, vol. 18, no. 11, pp. 3795 (1-18), Nov. 2018.
[13] Yang Miao, Wei Fan, Jun-ichi Takada, Ruisi He, Xuefeng Yin, Mi Yang, Jose Rodriguez-Pineiro, Andres Alayon Glazunov, Wei Wang, and Yi Gong, "Comparing Channel Emulation Algorithms by Using Plane Waves and Spherical Vector Waves in Multi-Probe Anechoic Chamber Setups," IEEE Transactions on Antennas and

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International Conference

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