Mobile Communications Research Group
Tokyo Institute of Technology

2021

ANNUAL REPORT

Contents

Tokyo Institute of Technology

Overview

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

Mission

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

Main Building (Honkan) with "Sakura".

Tokyo Tech Seal

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

Mobile Communication Research Group

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

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

MCRG Members

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

Core Laboratories

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

Cooperate Laboratories

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

Activities

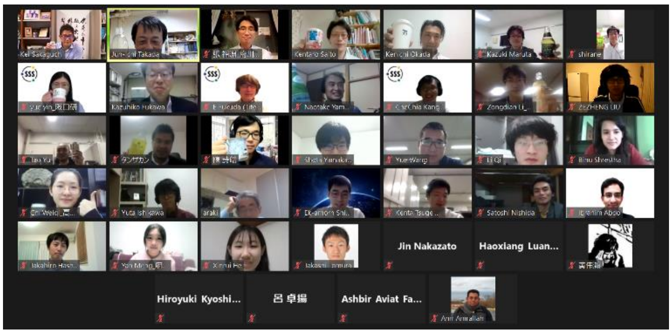
Beside the general research activities, for encouraging closer cooperation within MCRG and with the external companies, institutes and organizations, “Open House” and “Future Communication Research Workshop” are holed regularly. In addition, irregular invited speeches and lectures are also hold to broaden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

Future Communication Research Workshop

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

Open House

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



Takada Laboratory

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

Professor Jun-ichi Takada

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

Postdoctoral Researcher Nopphon Keerativoranan

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

Postdoctoral Researcher Sawaros Thanapornsangsuth

Dr. Sawaros (Sam) Thanapornsangsuth's research interests explore how education can be a foundational tool for sustainable development. Her goal is to study and promote a lifelong and innovative learning process that enables people to develop the knowledge, values, and skills. Driven by this goal, Dr. Thanapornsangsuth has extensive fieldwork experience in informal learning settings, both in the United States and abroad.

Dr. Thanapornsangsuth was a tenure-track lecturer at the Department of Education Policy, Management and Leadership, Chulalongkorn University in Thailand. She graduated with a Doctor of Education degree from the Communication, Media, and Learning Technologies Design Program at Columbia University (USA).

Takada Laboratory has investigated radio propagation research to realize the next-generation wireless communication systems and the localization and sensing systems by the radio wave. The recent topics are the millimeter-wave radio channel modeling for the Beyond-5G system and the millimeter-wave band dynamic spectrum sharing system. We also investigated the radio propagation model for a variety of scenarios such as drones, underground railways, underwater wireless sensors, Internet of Things (IoT) systems, and the rain attenuation in tropical regions. We are also developing the technologies that detect and measure the radio signals of the commercial wireless systems to understand the radio propagation characteristics in real environments.

Another research topic is the establishment of radio propagation simulation techniques. The recent issues are the physical optics approach, T-matrix based scattering modeling, and the propagation prediction by machine learning. We also studied the environment model construction techniques from camera images and laser scanners for those propagation simulation researches. The individual topics are as follows.

Recent Research Topics

- **Radio Spectrum Sharing Research**
  - Experimental Investigation of Energy Detector and Matched Filtering for Spectrum Sharing at High-Frequency Band
  - Minimum Path Loss Prediction Method for Spectrum Sharing in mm-Wave Band
  - Software Defined Radio based Cellular Signal Measurement System to Construct Interference Map for Spectrum sharing
- **Radio Propagation Simulation and Environment Modeling Research**
  - Radio Propagation Loss Prediction by Artificial Neural Network
  - Prediction of Diffuse Scattering Characteristics by Physical Optics Approach in 32 GHz band
  - Moving Object Tracking by Stereo Cameras for Dynamic Radio Propagation Simulation
- **Channel Sounding and Radio Propagation Research**
  - Study on the Characteristics of the Radio Channel in Subway Tunnel
  - Identification of Scattering Objects for 11 GHz Urban Microcell Radio Channel via Visual Inspection
  - Development of Hand Motion Tracking System using Channel State Information from Wi-Fi Devices
  - Prediction Method of Shadowing Effect by Complex-shape Object in mm-Wave Band
  - Radio Wave Propagation for Underwater Wireless Sensor Networks (UWSNs) Deployment
  - Theoretical Method Based Rain Attenuation Prediction for Millimeter-Wave Radio in Tropical Region

Takada Laboratory

Scenario-Based Radio Channel Modeling in Cyber-Physical Wireless Emulator [13, 16, 37]

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

Design, evaluation, and verification of a large-scale wireless system with high accuracy is essential prior to the implementation. Stochastic channel models are utilized for the link-level and system level simulations for the performance evaluation and the exhaustive drive-testing method is deployed for the validation. The former technique can be applicable for intra-system evaluation, but not suitable for inter-system interference in the realistic scenarios. The latter technique is time and cost inefficient. A cyber physical wireless emulator is to overcome drawbacks of both of these approaches. It emulates the real-world wireless network scenario in real-time, not only within cyber space but also with real or prototype radios via physical interface. Hence, scenario-based radio channel modeling framework is necessary for the implementation of the cyber-physical wireless emulator, which should have site-specific and system-independent features in either local/wide and stationary/dynamic scenarios, and which generates continuous and spatially-consistent channel responses.

Fig. 1 Scenario-based radio channel modeling

Grid-based Channel Emulation Technique for Development of Deterministic Radio Channel Emulator [10, 29, 33]

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

Radio channel emulator is an essential equipment for drive testing a large-scale wireless communication system with reproducibility result. Because of hardware constraint and real-time computation, deterministic channel model is not commonly applied for channel emulator due to high computational complexity despite its high accuracy.

Grid-based channel emulation is proposed to realize deterministic channel emulator. In this model, virtual space is divided into a grid structure where spatial channel parameters between base station (BS) and each grid node are simulated deterministically and stored in the emulator database. Then, time-variant channel of mobile station (MS) is synthesized by converting and interpolating the reference spatial parameters at grid node into temporal parameters at MS locations. Statistical characteristic of emulated channel was validated with ray-tracing (RT) result in office space both line-of-sight (LoS) and Non-LoS (NLoS) scenarios. Slightly discrepancy in terms of delay and Doppler spreads from those of RT were observed, thus maintaining statistic properties of the emulated channel.

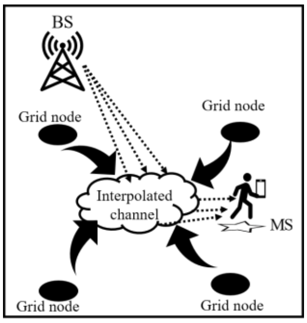


Figure 1 channel emulation architecture

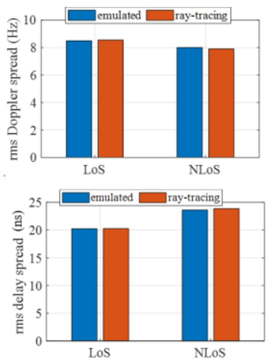


Figure 2 Doppler and delay spreads comparison in two scenarios

Low Computational Cost Mirror Kirchhoff Approximation [1]

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

This research proposes a 2-dimensional low computational cost mirror Kirchhoff approximation (MKA) and the design of simulation parameters to accurately predict the shadowing gain for an arbitrarily shaped conductor cylinder. The authors propose the design of the simulation parameters for MKA. The applicable range of MKA is extended to an arbitrarily shaped cylinder by multiple planes. This work finds that only the space domain of the zeroth plane and the angular spectrum domain of the last plane need separate windowing functions for accuracy and the calculation time. The authors validate the proposed method for an elliptical conductor cylinder with the size of the human body at millimeter waves. The results show that the proposed method presents a good accuracy, which has a low root-mean-square error of less than 0.5 dB by comparing it with a full-wave approach based on the method of moment (MoM). Furthermore, the calculation time is improved by 1.4 -- 67.2 times by comparing it with the uniform theory of diffraction (UTD).

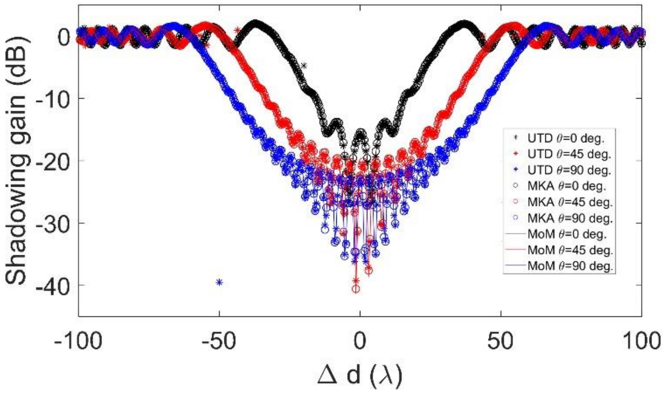
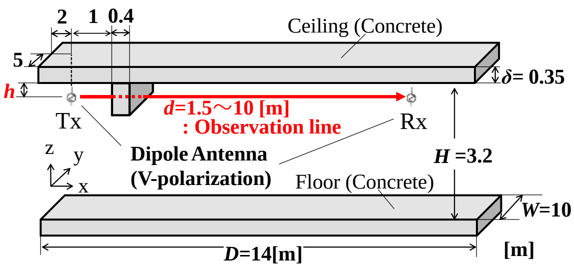


Fig. 1 Shadowing gain of elliptical conductor cylinder

Path Loss Prediction Formula in the 920MHz Based on FDTD Method close to Ceiling with Concrete Beam [34]

The purpose of this study is to provide a path loss prediction formula for IoT wireless communication close to ceiling beams in the 920 MHz band. The derivation of the formula was based on the simulation model, which assumes an actual building with ceiling beams shown in Fig.1. In the first step, simulations are conducted using the FDTD (Finite Difference Time Domain) method. As shown in Fig.2, the validity of the simulation model is demonstrated by comparing with measured results. In the second step, path loss prediction formulas are derived from the simulation results by dividing into three regions of LoS (line-of-sight) situation, the vicinity of the bottom of the beam, and NLoS (non-line-of-sight) situation, obstructed by the beam. For each condition, the prediction formulas were expressed in a relatively simple form as a function of *h*, the height of the antenna with respect to the beam bottom, using a least-squares best fit of the simulated result as shown in Fig. 2.

(a) Measurement site



(b) Calculation model

Fig. 1 Concrete beam ceiling model.

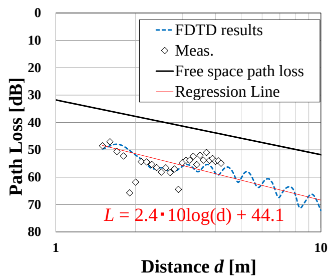


Fig. 2 Path loss characteristics in case of *h*=+0.6 m.

Takada Laboratory

Dynamic Shadowing Channel Sounding at 25 GHz band together with Posture Capturing [31]

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

Communication systems at millimeter wave (mmWave) band (24 GHz – 96 GHz) use active beamforming to compensate the high propagation loss. However, the highly directed propagation channel is fragile to dynamic objects, e.g., pedestrians and cars, caused sudden shadowing and fading. To evaluate and predict the impact brought by the dynamic blocking object, simultaneous dynamic channel sounding and posture capturing using RGB-D video camera, where the measurement time stamps must be synchronized, is needed

This study proposes the synchronization algorithm between two different instruments by using a visible laser. The blocking sensor of the laser beam triggers the spectrum analyzer. This trigger timing is synchronized with the first video frame, in which the laser spot appears on the surface of the blocking object. We have conducted the experiment by using a license-free transmitter at 25 GHz band and have confirmed the time synchronization was correct in the order of camera's frame rate.

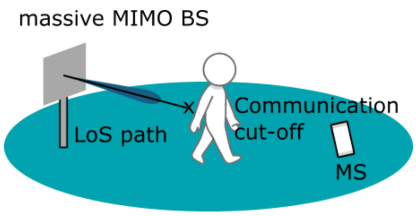


Fig. 1 Obstacle causing communication cut-off. searching algorithm.

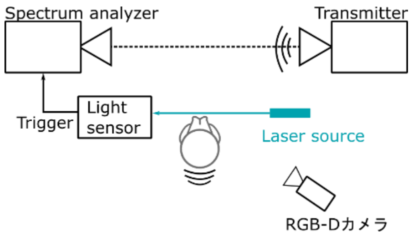


Fig. 2 Proposed dynamic channel sounder

Dynamic Human Body Shadowing Analysis in Millimeter Wave Band

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

With the explosive growth of mobile data demand, the fifth generation (5G) mobile network would exploit the enormous amount of spectrum in the millimeter wave (mm Wave) bands to greatly increase communication capacity. Compared with the sub-GHz band, the wavelength in mm Wave is relatively small, such that even the human body could significantly disrupt the communication link due to shadowing loss. Hence, dynamic modeling of the human shadowing in the mm Wave band is needed to predict the shadowing effect in the mm Wave communication.

Our subject is to analyze the shadowing effect caused by human blockage in terms of the change of received power at mm Wave bands. Human movement is captured by Kinect to establish a reconstructed model that is suitable for the simulation of the shadowing effect due to human motion. Double knife edge diffraction model (DKED) is used for pre-simulation.

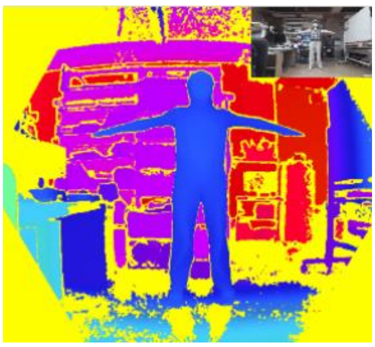


Fig.1 Human motion capture by Azure Kinect

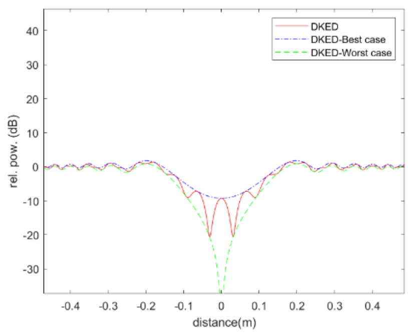


Fig.2 Simulation result at 28GHZ

Millimeter-Wave band Outdoor Measurement Under Tree Obstruction Scenario

(Supported by JSPS KAKENHI 19H02136)

With the increasing demand for higher communication data rates, new communication technology with higher data bandwidths has been a hot topic in the field. Due to the congestion in sub-6 GHz, the 5G wireless technology, also called New Radio (NR), at millimeter wave frequency has been intensively researched. While the high data rate communication is promising in NR, signals in mmWave band is more likely to be blocked by obstacles in the urban environment than signals in lower frequency band. Among all obstacles, vegetation is an inherent factor which can cause significant attenuation in the communication link.

In this work, a 5G base station mounted on the administration bureau buildings 1&2 and a gingko tree in front of it are targeted. The measurement goal is to investigate the shadowing effect caused by the gingko tree to the 5G signal. In the measurement, a cart with Rx (see Fig.1) moves along the trajectory which is 9m away from the tree, 25m away from Tx in a constant speed and receives signal from the base station. The position of Tx, Rx and tree is known by the point cloud which is scanned during the measurement. The changing level of SS-RSRP (Synchronization Signal reference signal received power), indicates the influence of the tree.

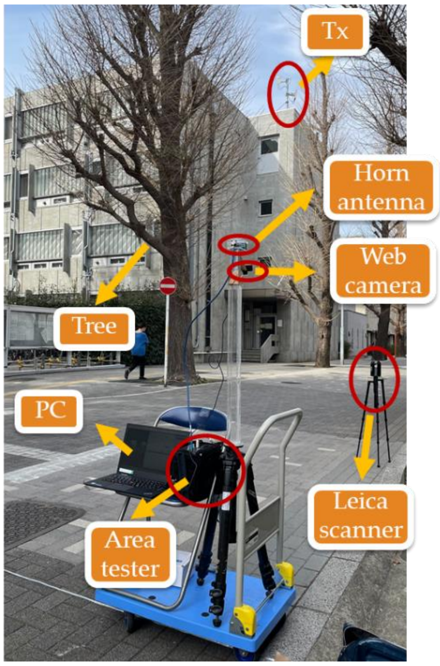


Fig.1 Cart setting

Knife Edge-Based Model for Attenuative Shadowing Estimation of Moving Vehicle [14]

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

Wireless communication near ground-level can be greatly attenuated when it is obstructed by a vehicle, especially at high frequency. Therefore, a sufficiently accurate and fast model for attenuative shadowing of a vehicle is needed for the development of a realistic propagation channel emulator.

The vehicle geometry is approximated as its bounding box for simplicity. The knife edge model with Bullington effective height recommended by ITU-R is used to estimate the loss over 3 edges in Fig. 1. The diffraction path with the lowest attenuation is considered as the estimation of the total loss. The method of moment (MoM) in 2D is used to preliminarily validate the model. The simulation results are shown in Fig. 2 showing that the model significantly underestimate the loss at deep shadowing when compared to the MoM. The results suggest that the discrepancy comes from the object thickness. Fast fading is also observed at deep fading, so multiple diffraction paths should be considered.

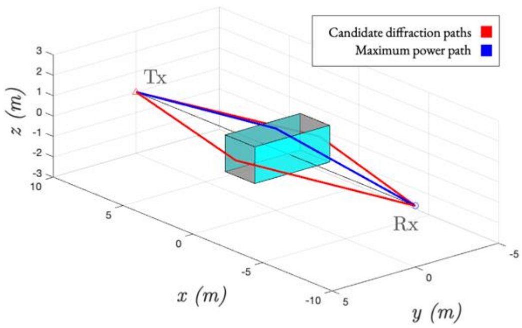


Fig. 1 proposed model.

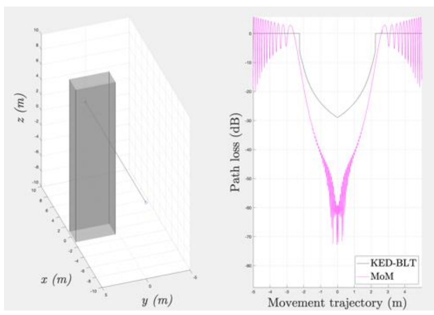


Fig. 2 preliminary result and validation in 2D

Takada Laboratory

Verification of Passive Channel Sounder with the Measurement of Path Loss in Line-of-Sight Condition [28]

(Supported by JSPS KAKENHI 19H02136)

It is necessary to verify channel sounder before carrying out actual measurement. While over-the-air channel verification is often done in anechoic chamber, it is impractical to do so for passive channel sounder. Therefore, over-the-air channel measurement in the line-of-sight (LOS) condition is considered in an open space for verification purpose. Since open space might lead to multi paths, this work presents extraction of LOS path loss from measurement of ground reflected two paths in the open space using passive channel sounder and its comparison with theoretical value.

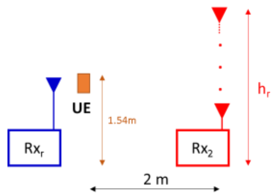


Fig. 1. Measurement Setup

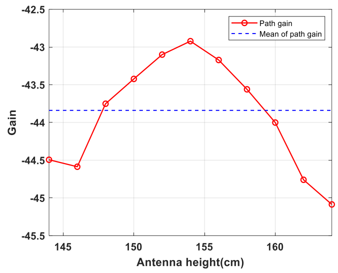


Fig. 2. Measurement result

Measurement was conducted in front of south 6, Ookayama campus, Tokyo tech by varying receiver antenna height from 1.44 m to 1.64 m as shown in Fig. 1. Channel sounder consists of mobile router operating in UMTS network as transmitter and two software defined radios (SDR) consisting of USRP and GNU Radio in receiver side. From the experiment, path loss of LOS component, estimated by taking an average of path loss of the two paths over one period was found to be 43.84 dB. This result is found to be consistent with the 44.38 dB, free space path loss at 2 m.

Device-free Single-Person Indoor Localization Using Wi-Fi Channel State Information [27]

Indoor localization is essential to applications such as navigation and remote healthcare services. Due to ubiquity, Wi-Fi-based indoor localization technique utilizing channel state information (CSI) has been intensively studied. In this work, we leverage the micro-Doppler effect caused by the chest movement during respiration to determine the location of a single human target. First, Doppler filtering is performed to extract the dynamic component of CSI due to chest movement. Then, the minimum-variance distortionless response (MVDR) filter is applied to the CSI dynamic component to obtain super-resolution power delay profile (PDP). The mean delay from first peak of the PDP is calculated and used as the location fingerprint. Pattern matching using Euclidean distance with Doppler power as the weight average was then performed to estimate location of the target.

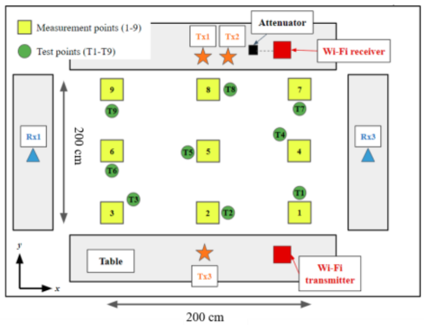


Figure 1 Schematic of measurement scenario

The measurement was conducted in a meeting room using two laptops as Wi-Fi transmitter and receiver with spatially-distributed antennas shown in Fig. 1. Localization performance of nine tested points were evaluated with sub-meter distance error at the median.

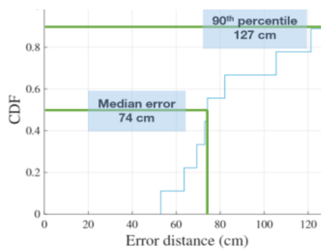


Figure 2 CDF of localization error

A Novel Parameter Estimation and Tracking Method Based on Distributed Sensors

The authors proposed a new distributed sensors-based for parameter estimation and tracking in terms of the abstract models of factor graph (FG). With proposed distributed sensors network technique, each sensor will do the processing for compression and send the compressed results to the fusion center. The marginalization of the compressed sensing results can be calculated over the FG in the fusion center. In addition, a maximum a posteriori probability (MAP) can be achieved during the tracking phase through the FG. The MAP over FG will be used for predicting next state of parameter estimation by unified extend Kalman filter (EKF) based FG to improve the estimation accuracy without high computation effort.

The whole iteration process is extremely simple which fast convergence can be achieved even the initial guess is far away from the true value. Moreover, the proposed technique can be applied to any kind of nonlinear model, and multi-parameter prediction and tracking can be achieved for multi-input and multi-output (MIMO) systems.

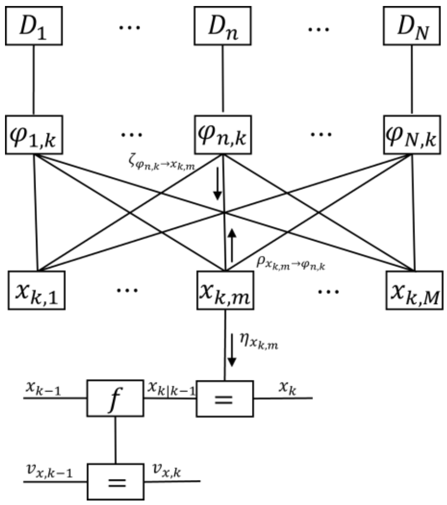


Fig. 1. Distributed sensors-based FG

Design of passive reflectors for illumination of shadowed regions in 28 GHz

The basic challenges of exploring the spectrum in the range of millimeter waves (mm-waves) band, is high penetration loss. In urban area trees can be very important obstacles the simulation scenario is shown as fig.1. To avoid the penetration loss caused by trees, one idea is using passive reflectors to create another path for signal to propagate. However, traditional reflectors such as flat reflectors have a small coverage area.

In this research, we research other types of reflectors such as cylindrical and spherical reflectors to get larger coverage area. We also design a new type of reflectors called ellipsoid reflectors which have the best coverage in our model. The simulation results of each type of reflector is shown as figure 2. We can find ellipsoid reflectors have double coverage area compares to flat reflectors.

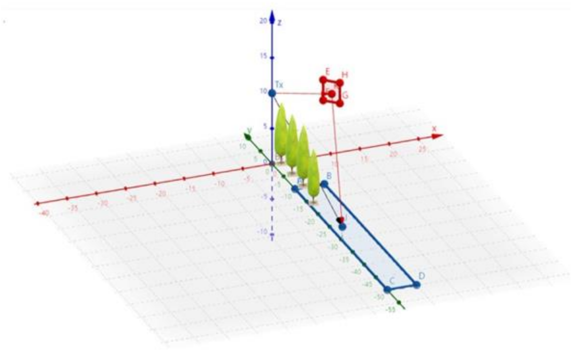


Fig.1 simulation scenario

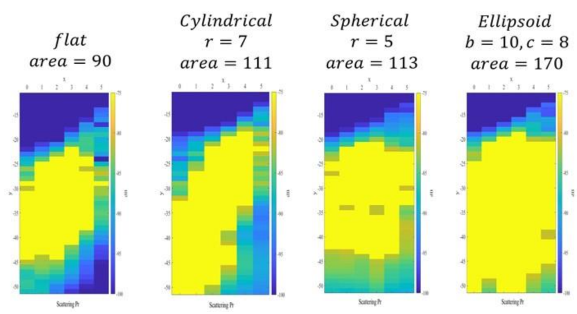


Fig.2 Simulation results

Professor Kei Sakaguchi

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

Associate Professor Gia Khanh Tran

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

Emeritus Professor Kiyomichi Araki

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

Specially Appointed Assoc. Prof. Kazuki MARUTA

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

Sakaguchi-Tran Laboratory

Tokyo Tech Private Beyond 5G/6G Network

In conventional, Sakaguchi-lab proposed a concept based on the combination of ultra-broadband millimeter wave (mmWave) communication and edge cloud in the 5G-MiEdge Project. As a result, several mmWave small cell base stations are equipped with an edge cloud distributed over a legacy macrocell. Following some of the above content, we constructed an experimental field as shown in Fig. 1. In this figure, Edge Cloud holds the virtualization platform that connects the physical space and cyberspace, and the wide-area and the local area are deployed in the physical space. PoC use cases can be Digital Twin, V2X, AR/VR/MR, etc. Here, in the Edge Room, we build a virtualization platform giving attention to application requirements. If the Edge Cloud is mobile-only, it is expected to reach the service realization level in E2E. Moreover, since it can accommodate local networks, it is possible to research and develop next-generation networks involving massive sensor networks.

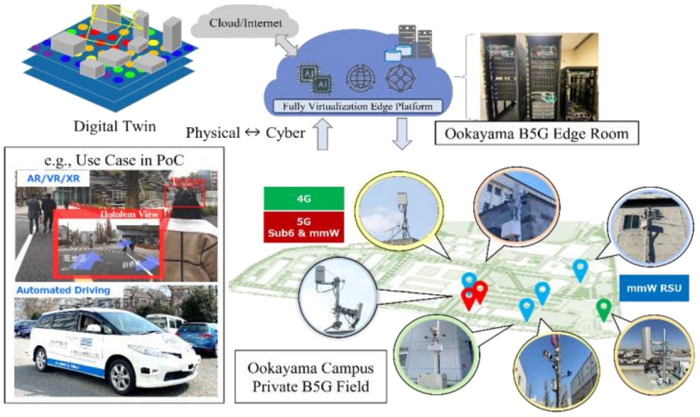


Fig. 1 B5G/6G Proof-of Concept Field in Campus

The low-frequency band covers the entire area in terms of the system hierarchy. A 5G NR (New Radio) network with Sub6/mmWave and a wireless network at 60GHz in the higher frequency band are constructed on the overlay. This network is called Private B5G Field. In this field, users can use advanced networks as clay pipes without knowing which network they are connected to. Applications are distributed according to use cases to Edge Cloud or the cloud. Utilizing this field, we will further develop technologies for B5G/6G and enhance standardization, overseas collaboration, and competitiveness.

Tokyo Tech MmWave B5G with Relay

The 5th generation mobile communication (5G) is now in service in many countries around the world. higher speeds can be achieved by introducing beamforming and millimeter wave (mmWave) bands. However, since the mmWave band has a narrow transmission range, it is necessary to develop an efficient service area using relay stations based on a detailed understanding of the propagation environment of mmWave.

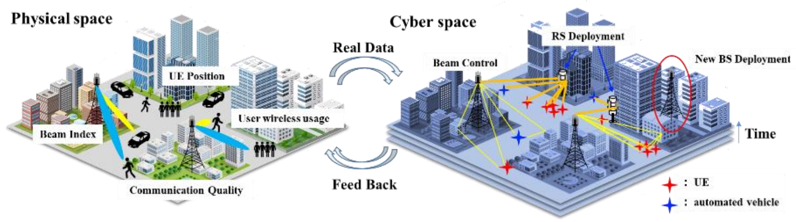


Fig. 2 mmWave Area Deployment System

Consequently, we propose an area design that can reproduce the propagation environment in real-time using digital twin and dynamically determine the deployment of the repeaters. Fig. 2 shows the architecture of the mmWave area deployment system proposed in this study. In the physical space, base stations are installed, and coverage is deployed according to users by beamforming. The information such as which beam is controlled for which user is recognized as digital information in the cyber space of the digital twin platform and the appropriate placement design of relay stations is fed back to the physical space in real-time. As a result, frequency coexistence without interference to existing base stations and efficient deployment of mmWave area can be realized.

MmWave Massive Relay SU-MIMO

Millimeter-wave (mmWave) communication is a key technology to realize ultra-high data-rate and ultra-low latency wireless communications. The mmWave communication employs a higher frequency band which allows a wider bandwidth and is suitable for large capacity communications. However, due to the strong diffraction loss and the path loss in the mmWave band, it is difficult to achieve high channel capacity for user equipments (UEs) located in Non-Line-Of-Sight (NLOS) environments.

MmWave Analog Relay SU-MIMO can generate MIMO channel response artificially by using a large number of analog relay stations (RSs). The system enabled MIMO transmission, which was difficult to achieve in mmWave. The analog RS node has two sides, a receiving side, and a transmitting side, in both of which the beamforming can be actively performed according to the location of the UE in real-time. we adopt the Amplify-and-Forward type to reduce the delay of data transmission. By relaying the signals by a large number of RSs, an artificial MIMO propagation environment can be formed, which enables mmWave MIMO communication to the NLOS environment. The numerical results show that the proposed system achieves high data rates even in a grid-like urban environment.

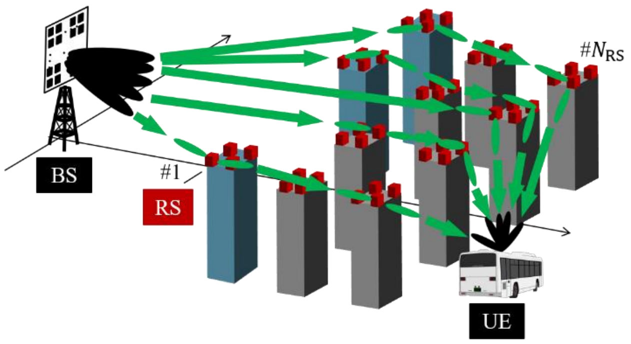


Fig. 3: Massive Relay SU-MIMO System

MmWave Massive Relay MU-MIMO

Different from the mmWave Analog Relay SU-MIMO system, users need to share the resource of RSs and streams in the mmWave Analog Relay MU-MIMO system. So, we use algorithms to distribute the resource of channels and optimize BS directivity fairly to improve the channel capacity for each user.

We use block diagonalization to separate signals from the base station to different users and avoid interference in the system. For the directivity of the base station, determine the base station directivity from the channel capacity cumulative density distribution based on the Proportional Fair standard, a distribution close to the throughput maximization standard can be obtained. And the cumulative whip distribution value of users' distribution who have difficulty in acquiring the channel capacity can be improved by up to 1 Gbps. On the other hand, the channel capacity decrease when users are close to each other is a major drawback in the Proportional Fair standard. We considered allocating resources to a single-user environment for each user and a multi-user environment including all users. By using this Resource block assignment, improvement is confirmed in the area where the channel capacity decreases in a multi-user environment, and this model can be expected to improve the channel capacity by up to 4 Gbps for one user.

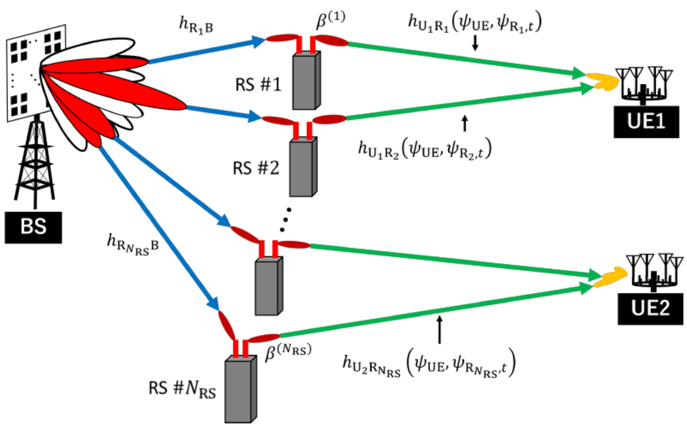


Fig. 4. Massive Relay MU-MIMO System

Sakaguchi-Tran Laboratory

5.7GHz Multi-UAV Full-duplex Communication System Design and Experiement

To address the issues in multi-UAV communication systems, such as limited energy/payload and severe interferences in aerial channels, we proposed a multi-UAV full-duplex communication system, as illustrated in Fig. 5. The uplink and downlink of each employ separate channels, so that the self-interference canceller in conventional full-duplex systems is not necessary. To increase the radio resource efficiency, each channel is assigned to uplink and downlink two different UAVs. To mitigate the co-channel interference, high-gain directional antennas are employed in GS and UAVs. Therefore, a system-level full-duplex UAV system with low hardware complexity has been achieved.

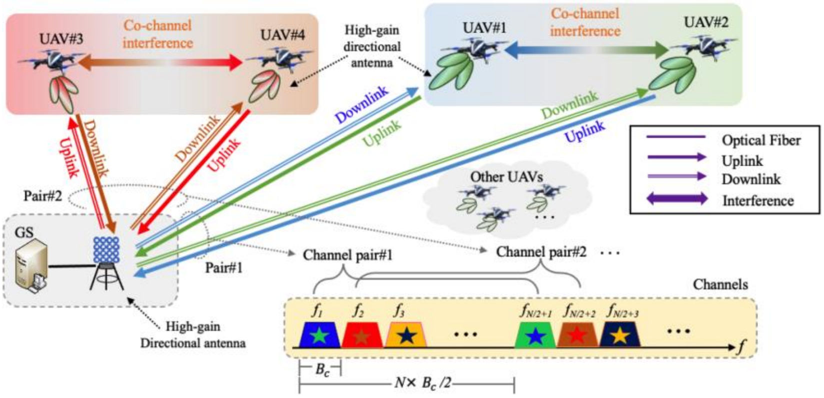


Fig. 5. Multi-UAV Full-duplex Communication System

The side lobes of UAVs and GS antennas can also effectively suppress the co-system interference to terrestrial systems using the same bands, as shown in Fig. 6. Moreover, by defining the flyable area of UAVs in advance of UAV operation according to radio map of terrestrial systems, efficient UAV operation and spectrum sharing can be achieved, and UAV transmission can be done in continuous manner without the carrier-sensing before transmission.

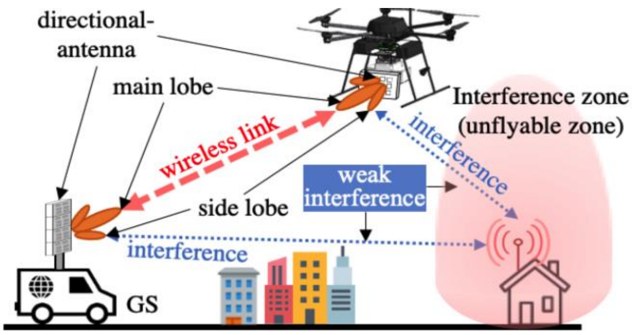


Fig. 6. Spectrum sharing with terrestrial systems

The experimental prototype system (including baseband processing, wireless transceivers for UAVs/GS, refitted UAVs, directional antennas and gimbles) is practically developed, and it aims to support 4K video transmission in real-time (E2E latency smaller than 100ms) at maximum distance of 5km from 10 UAVs at 5.7GHz band (total bandwidth: 105Hz, 10 channels). Validation experiments were conducted in the coast of Fukushima, as shown in Fig. 7. In the experiment, 4K video was successfully transmitted from UAV at 100m and 150m in height and 5km away. The co-system interference is also measured, and it confirms that the interference area is small and agrees well with the theoretical analysis.

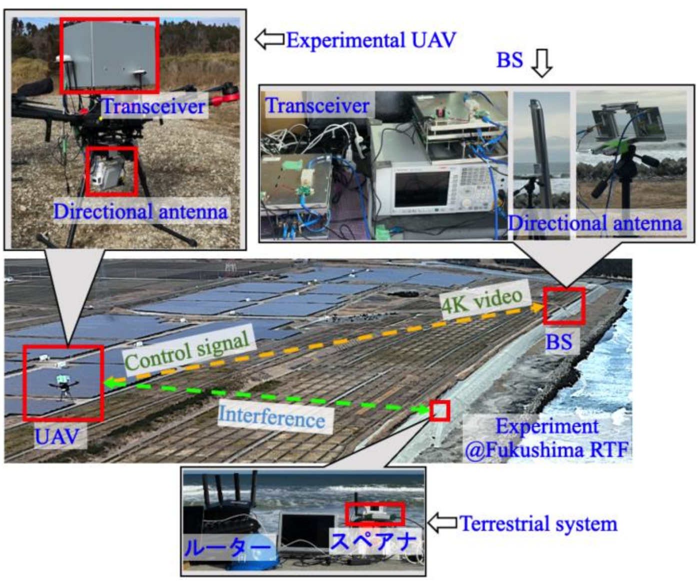


Fig. 7. Experiment

Smart Mobility R&E Field in Tokyo Tech

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

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

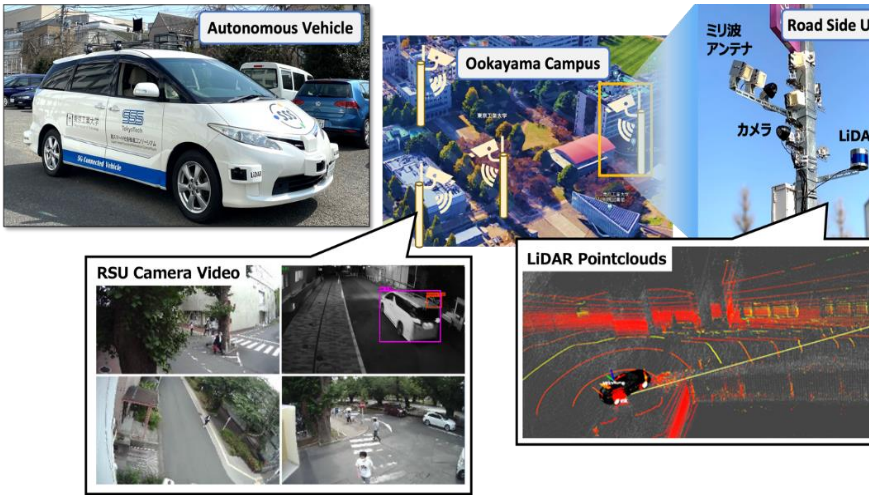


Fig. 8 Facilities of Smart Mobility R&E Field

Radio Resource Management for MmWave V2V

Millimeter-wave (mmWave) Vehicle-to-Vehicle (V2V) communication system has drawn attention as a critical technology to extend the restricted perception of onboard sensors and upgrade the level of vehicular safety that requires a high data rate. However, co-channel inter-link interference causes significant challenges for scalable V2V communications. To overcome such limitations, this paper firstly analyzes the required data rate ensuring maneuver safety via mmWave V2V relays in an overtaking traffic scenario. Based on these preparations, we propose a distributed radio resource management scheme that integrates spatial, frequency, and power domains for two transmission ranges (short/long).

In the spatial domain, ZigZag antenna configuration is utilized to mitigate the interference, which plays a decisive role in the short inter-vehicle distance. In frequency and power domains, two resource blocks are allocated alternately, and transmit power is controlled to suppress the interference, which has a decisive impact on interference mitigation in the long inter-vehicle distance. Simulation results reveal that the achievable End-to-End (E2E) throughput maintains consistently higher than the required data rate for all vehicles. Most importantly, it works effectively in scalable mmWave V2V topology.

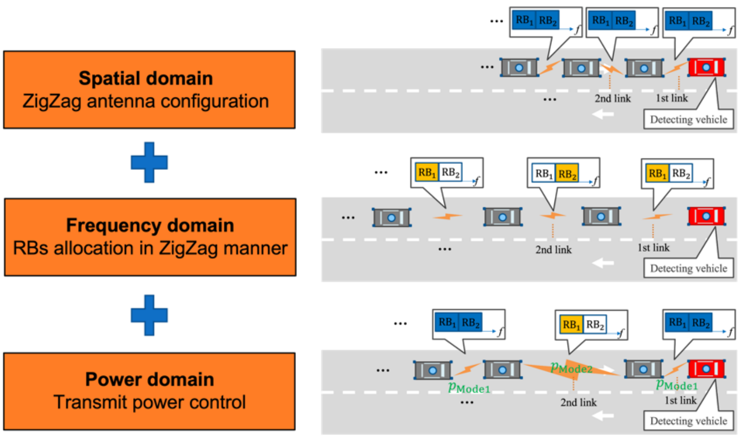


Fig. 9. Basic Concept of RRM Scheme

Sakaguchi-Tran Laboratory

Optimal Network Management for UAVs

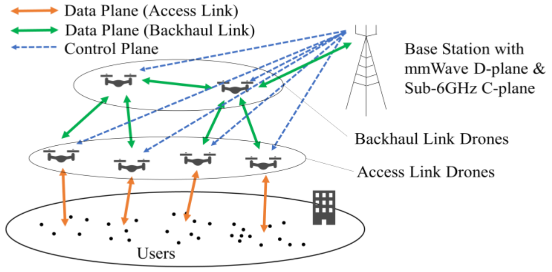


Fig. 10. UAV Network

Due to the development of information technology and the associated increase in traffic volume, more requirements for communications are expected in terms of both data rate and coverage. For this reason, the use of airborne base stations with UAVs has been proposed. Airborne base stations can be placed freely without being affected by the ground environment and can be operated flexibly in both space and time. In addition, there are fewer obstacles in the sky, and the coverage increases due to less attenuation. For this UAV network, we are considering the use of millimeter waves owing to its wideband performances. This year, we have been working on the problem of access UAV placement and interference avoidance between access link backhaul links, as well as an experimental demonstration.

In this year's study, we simulated the placement problem of access UAVs by using a model closer to real environments. First, we used a user distribution taking into account users' mobility. We proposed a method to reduce the power consumption of the UAV by considering the user movement. In addition, we used a model which takes into account the effect of shielding by buildings. By using the model, we proposed a method of reallocating the UAV to avoid obstruction.

We also build an experimental system of millimeter-wave UAV base station to provide users with temporary and high capacity networks. The results validated the effectiveness. Furthermore, experimental results also revealed the effect of ground reflection when there are multiple UAV BSs.

AI-based Radio Resource Management for UAV Wireless Networks

Fig. 11 UAV surveillance-system-assisted DSA for a metropolitan post-disaster area

Modern wireless networks are notorious for being very dense, uncoordinated, and selfish, especially with greedy user needs. This leads to a critical scarcity problem in spectrum resources. The Dynamic Spectrum Access system (DSA) is considered a promising solution for this scarcity problem. With the aid of Unmanned Aerial Vehicles (UAVs), a post-disaster surveillance system is implemented using Cognitive Radio Network (CRN). UAVs are distributed in the disaster area to capture live images of the damaged area and send them to the disaster management center. CRN enables UAVs to utilize a portion of the spectrum of the Electronic Toll Collection (ETC) gates operating in the same area as shown in Fig. 11. In this research, a joint transmission power selection, data-rate maximization, and interference mitigation problem is addressed. Considering all these conflicting parameters, this problem is investigated as a budget-constrained multi-player multi-armed bandit problem. The whole process is done in a decentralized manner, where no information is exchanged between UAVs. To achieve this, two power-budget-aware (PBA-MAB) algorithms were proposed to realize the selection of the transmission power value efficiently. The proposed PBA-MAB algorithms show outstanding performance over random power value selection in terms of achievable data rate and interference mitigation.

UAV based Localization Networks

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

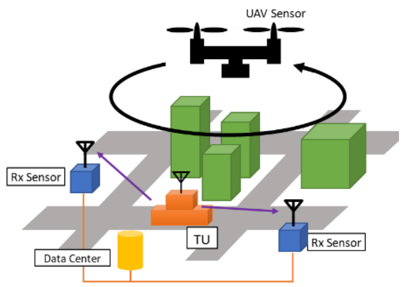


Fig. 12 Localization using UAV senser

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

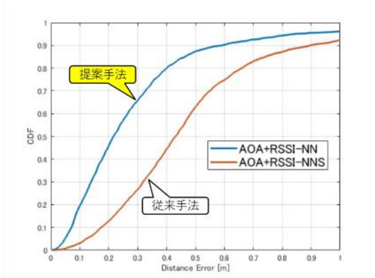


Fig. 13 Localization with Neural Networks

Fig. 14 Experiments using line tracers

Antenna System Design for WLAN

When a MIMO antenna is created using multiple antenna elements, if each antenna is randomly arranged in one terminal, the gain obtained by antenna coupling may vary. This makes it difficult to achieve the maximum efficiency throughput of the MIMO antenna.

When designing and installing an access point, properly design it according to the environment, taking into consideration antenna coupling, etc. within the constraints of installing antennas with different antenna intervals and different frequencies in the same terminal. It is necessary to choose the installation location.

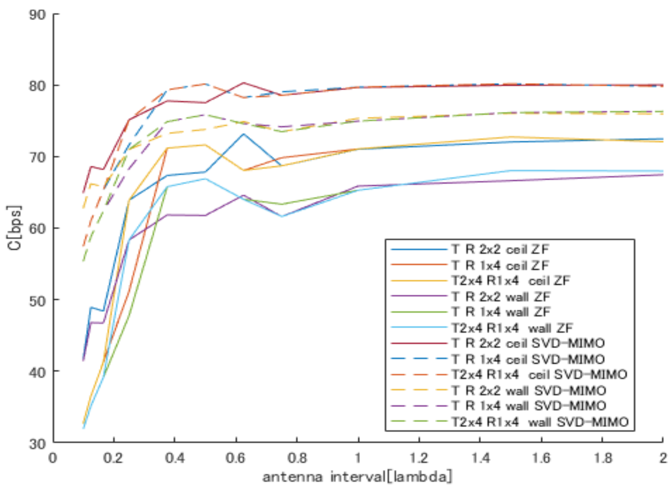


Fig. 15. Comparison of antenna spacing of dipole antennas and communication capacity for each coding method

In this year, we model the actual environment and consider the MIMO communication capacity characteristics for each antenna interval when using an arrayed antenna system such as 1x4, 2x2, and 2x4 dipole antennas.

Hirokawa Laboratory

Hirokawa LABORATORY

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

Professor Jiro Hirokawa

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

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

Assistant Professor Takashi Tomura

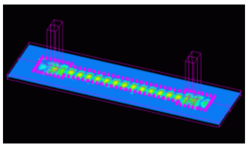
received the B.S., M.S. and D.E. degrees in electrical and electronic engineering from the Tokyo Institute of Technology, Tokyo, Japan, in 2008, 2011 and 2014, respectively. He was a Research Fellow of the Japan Society for the Promotion of Science (JSPS) in 2013. From 2014 to 2017, he worked at Mitsubishi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

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

Our Research Interests

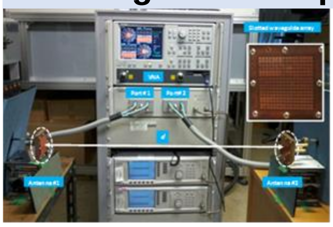
Hirokawa laboratory have researched antennas, feeding circuits, electromagnetic analysis theory and wireless communication systems. Main target frequency band is millimeter wave band and higher band such as 120 GHz and 350 GHz. The features of our antennas are planar, high gain, high efficiency and wide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

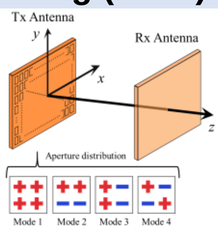
Post-wall waveguide



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

Rectangular coordinate orthogonal multiplexing (ROM)

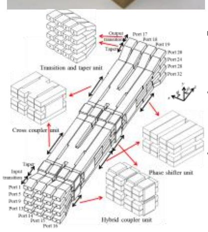




- Published in the IEEE transaction in 2017
- Equivalent to OAM transmission in the optical communication system, and apply to microwave and millimeter-wave applications

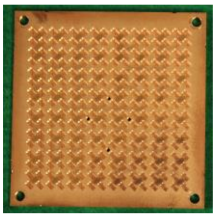
2-D beam-switching one-body Butler matrix

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

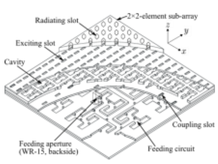


- $4^2 \times 4^2$-way one-body 2-D beam-switching waveguide Butler matrix
- Reduced its length and conduction losses by half.
- Reduced the number of components and volume.

Corporate-feed Slot Array Antenna with Plate-laminated Waveguide

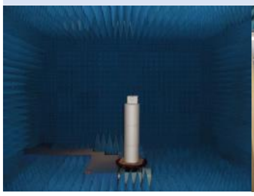


- Published in the IEEE transaction in 2011.
- After that, research is also started in Sweden, Singapore, China, etc.
- Designed in various frequency bands like 38-GHz band, 60-GHz band, and 120-GHz band, etc.

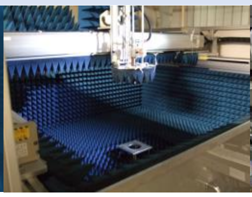


- ✓ Large number of elements ⇒ High gain
- ✓ Made with metal only ⇒ High efficiency
- ✓ Composed of the corporate-feed circuit ⇒ Wide band

Measurement Facility



Anechoic Chamber



Near Field Measurement

Vector Network Analyzer

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

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

Hirokawa Laboratory

60-GHz-wave-band multiplexed wideband wireless link using rectangular-coordinate orthogonal multiplexing (ROM) antennas

Rectangular-coordinate orthogonal multiplexing (ROM) is one of space multiplexing transmission methods as well as Orbital angular momentum (OAM). ROM uses polarity difference over antenna aperture whereas OAM uses phase rotation. Magic-tees enable wideband generation and separation of ROM modes because of their structure property. Therefore, ROM modes can be generated and separated over wide frequency band using hardware. OAM suffer from limited bandwidth of hardware separation and generation of modes and requires software processing to improve isolation among modes. ROM is suitable for high-speed and high-frequency wireless multiplexed transmission such millimeter and THz wave band. We have developed four- [1] and eight-mode [2] ROM antennas.

In this paper, we have introduced 60-GHz ROM antennas [3] on a photonics-enabled real-time wireless data transmission, transmitting over two channels simultaneously, without any signal processing at the transmitter (multiplex) or the receiver (demultiplex) [4]. The two multiplexed channels show a total data rate up to 9.0 Gbps at most (5.875 Gbps and 3.125 Gbps for each channel) limited by the bandwidth of the low noise amplifiers at the receiver. The measured bit error rate (BER) is below the forward error correction (FEC) limit.

This work was supported in part by SEI Group CSR Foundation and the Murata Science Foundation.

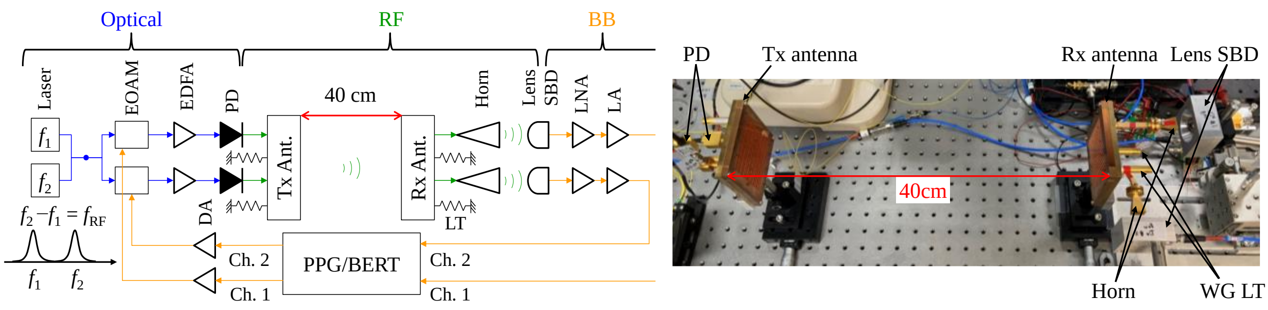


Fig. 1 Wireless Transmission Test Configuration [4]

Referrence

[1] K. Tekkouk, J. Hirokawa, and M. Ando, “Multiplexing antenna system in the non-far region exploiting two-dimensional beam mode orthogonality in the rectangular coordinate system,” IEEE Trans. Antennas Propag., vol. 66, no. 3, pp. 1507–1515, Mar. 2018.

[2] K. Wada, T. Tomura, and J. Hirokawa, “Dual-polarized two-dimensional beam mode orthogonal multiplexing antenna system for the non-far region,” IEEE Trans. Antennas Propag., vol. 68, no. 9, pp. 6614–6623, Sep. 2020.

[3] R. Ohashi, T. Tomura, and J. Hirokawa, “Transmission enhancement in rectangular-coordinate orthogonal multiplexing by excitation optimization of slot arrays for a given distance in the non-far region communication,” IEICE Trans. Commun., vol. E103-B, no. 2, pp. 130-138, Feb. 2020, [Online] Available: https://t2r2.star.titech.ac.jp/rrws/file/CTT100816214/ATD100000413/

[4] T. Tomura, J. Hirokawa, M. Ali, and G. Carpintero, “Millimeter-wave multiplexed wideband wireless link using rectangular-coordinate orthogonal multiplexing (ROM) antennas,” J. Lightw. Technol., vol. 39, no. 24, pp. 7821–7830, Dec. 2021. DOI： 10.1109/JLT.2021.3093445

Reception Level in a Touchless Ticket Gate Including the Element Pattern in the Millimeter-wave Band Waveguide Slot Array Installed on the Sides

This work was supported in part by SEI Group CSR Foundation and the Murata Science Foundation.

One of the touchless entrance control gates is a system in which an antenna on the ceiling of an entrance control gate radiates a millimeter-wave to the floor side and communicates with an admission pass to open the gate. However, the millimeter-wave from the ceiling is sometimes blocked by a passenger's body and luggage and do not reach the admission pass. Therefore, additional antennas should be installed on the sides of the gate so that they will not be blocked. The beam radiated by the side antenna should be higher than the minimum operation level in the entrance control gate and lower than the given interference level outside the entrance control gate. We investigate a proper beam width and power of the antenna considering the element pattern.

A model of the entrance control gate was created and the proper beam width at 60.48 GHz was obtained by Ray-Tracing. Since it is desirable to have a more uniform power distribution within the entrance control gate, we design a pattern with a transmit power of -15 dBm and (φ, θ) = (9°, 5°) (φ: Horizontal beam width, θ: Vertical beam width).

To design an array antenna with beamwidth (φ, θ) = (9°, 5°), the element array of the antenna is obtained. As a result, it was found that a (φ, θ) = (9.2°, 4.8°) beam can be achieved with an array antenna consisting of the 2×2-element antenna is used as an 8×4 pair-excited Taylor distribution. This is because the antenna we will use is a corporate-feed antenna with 2×2 elements as a sub-array.

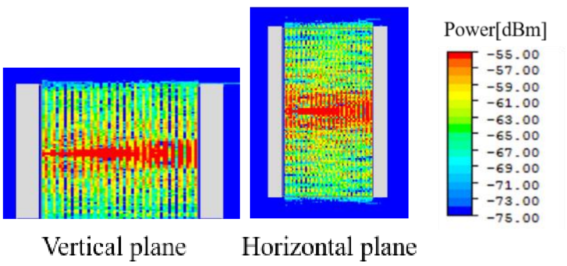


Fig. 1 Power Distribution by an Array Antenna Beam

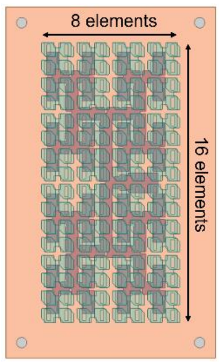


Fig. 2 Antenna Structure

Referrence

[1] 黒瀬瑞輝，戸村崇，広川二郎，“タッチレス改札の側面に設置したミリ波帯導波管スロットアレーによる受信レベルの制御”，信学技報，vol. 120，no. 171，AP2020-45，pp. 66-70，2020-9.

[2] M. Kurose，T. Tomura and J. Hirokawa，“Reception level in a touchless ticket gate including the element pattern in the millimeter-wave band waveguide slot array installed on the sides”，Intl. Symp. Antennas Propag., Oct. 2021.

Hirokawa Laboratory

Analysis and design of a circularly-polarized element on a parallel-plate waveguide with perpendicular corporate-feed

We report on the frequency characteristics of wideband reflection and axial ratio in the 60 GHz band by the design of a circularly-polarized element on a parallel-plate waveguide with perpendicular corporate-feed. In a conventional corporate-feed waveguide circularly polarized slot array antenna [1], plural thin metal plates are stacked and diffusion bonded [2]. A problem is that the number of the plates is large due to the metal-wall cavity and the thick degenerated apertures in the radiation part. To solve this problem, we propose the radiation part in which plural thin layers of degenerated apertures are stacked with spaces among them without bonding. We aim to simplify the structure and maintain the characteristics. Conventionally, we designed using a general-purpose software (HFSS). However, because of a large number of parameters and huge amount of time required for the analysis, we create a fast analysis program using the method of moments specified for the structure, and use a genetic algorithm for broadband design.

Fig.1 shows the antenna structure. The antenna consists of four layers: a straight slot layer on the broad wall of a rectangular waveguide, two hexagonal slot layers, and a circular slot layer. This circular slot layer distributes the power from one element to 2 x 2 elements. There is an air layer between each slot layer and no electrical connection. Two pairs of periodic boundary walls are provided on the side walls to consider the mutual couplings in a uniformly-excited two- dimensional array.

As a result, 13.0% bandwidth for VSWR less than 1.5 and axial ratio lower than 3 dB are obtained with a small number of thin metal plates. In addition, the analysis time is reduced by 90.3% compared with general-purpose software. In addition, conventional diffusion bonding is no longer necessary in the radiating part. Furthermore, the thickness of the metal plates of the radiating part is reduced from 6.80 mm to 1.15 mm.

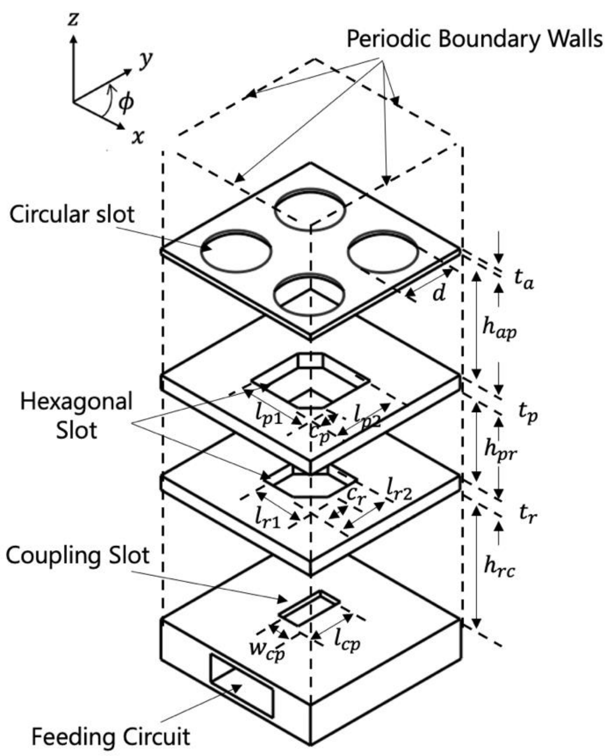


Fig. 1 Antenna structure

Referrence

[1] 和井秀樹, 戸村崇, 広川二郎, “縮退分離六角形断面導波管円偏波放射開口アンテナの不要共振除去設計, ” 信学技報，AP2018-102，2018 年 11 月.

[2] R. W. Haas, D. Brest, H. Mueggenburg, L. Lang, and D. Heimlich, “Fabrication and Performance of MMW and SMMW Platelet HornArrays,” International Journal of Infrared and Millimeter Waves, vol.14, no. 11, pp. 2289-2294, Sep. 1993.

[3] 西本広希，戸村崇，広川二郎．垂直並列給電多層平行平板円偏波放射素子の解析と設計，電子情報通信学会，アンテナ・伝搬研究会，信学技報, vol. 121，no. 330，pp. 86-91，Jan. 2022.

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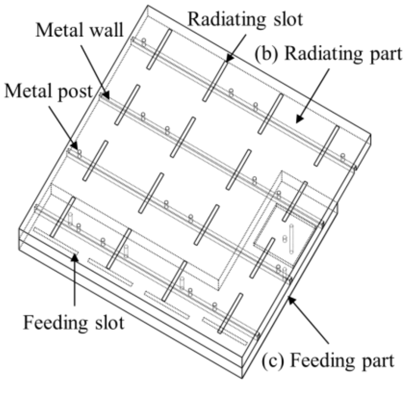
Design of a Slot Array Antenna on Alternating-phase Feed Parallel-plate Waveguide

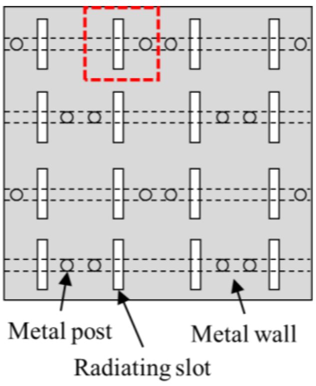
Since the antenna for wireless power transmission for solar power generation in space becomes a very large array, the sub-arrays should have a simple structure. In a waveguide slot array antenna with alternating-phase feed between the adjacent waveguides, the side walls can be removed by considering the current distribution. As a result, a parallel plate waveguide is composed. Various structures have been proposed to excite radiating slots in co-phase in the alternating-phase feed. However, when the slots are offset to each other at intervals of a half guided wavelength, undesired second-order lobes are radiated. To suppress them, no slot offset is introduced, and a metal post is installed near the slot for excitation. Standing wave excitation is used to apply to a narrow-band and small-element array. A metal wall is also introduced to represent only by a parallel conductance on the equivalent transmission line, which simplifies the array design.

The proposed antenna configuration is shown in Fig.1. It is a 4×4-slot array antenna, which has a dual-layered structure of a feeding part and a radiating part. The feeding part has feeding slots with offset spaced by a half guided wavelength intervals for alternating-phase feed to the radiation part. A metal post is introduced for each feeding slot to eliminate the susceptance of a parallel admittance on the equivalent transmission line. The radiating part has radiating slots without offset. The slot is excited by a metal post in the vicinity. A metal wall is added at the bottom at eliminates the susceptance of a parallel admittance on the equivalent transmission line. The metal posts also contribute to heat dissipation in solar power generation.

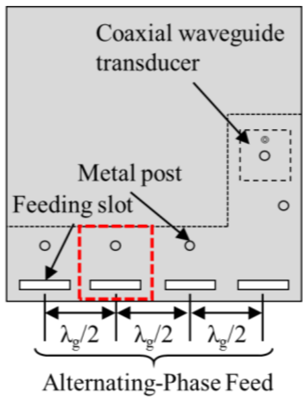
The overall structure in Fig.1 (a) is designed and simulated by introducing periodic boundary walls in the external region to include the mutual couplings in an infinite uniformly-excited array for a large array in solar power generation in space. The design frequency is 5.8 GHz, the size of the antenna is 146.2 mm × 146.2 mm × 12.3 mm, and the plate thickness is 0.1 mm. As results, the reflection is -33.8 dB, the directivity is 19.7 dBi, and the aperture efficiency is 92.7 % at the design frequency of 5.8 GHz.



(a) Overall structure



(b) Radiating part



(c) Feeding part

Fig. 1 Antenna structure

Referrence

[1] Y. Ishikawa, T. Tomura, and J. Hirokawa, "Design of a Slot Array Antenna on Alternating-phase Feed Parallel-plate Waveguide," Intl. Symp. Antennas Propag., 220266, Oct. 2021.

[2] 石川裕太，戸村崇，広川二郎，"逆相給電平行平板導波路スロットアレーアンテナの設計，" 信学総大，B-1-89，2021-3.

Bandwidth Enhancement of a Two-plane Coupler by Changing the Cross-sectional Shape of the Coupling Region

A two-plane hybrid coupler is a coupler that equally distributes the power from the input port to the output port, and a phase difference of 90 degrees occurs between adjacent ports. This is a one of the key elements of the 2D beam-switching Butler matrix. However, the conventional two-plane coupler hybrid coupler had a narrow bandwidth, which caused the overall bandwidth narrow. To overcome this problem, we made a change to the structure and used Genetic algorithm to define parameters of the model.

The two-plane hybrid coupler designed in a previous study is shown on the left in Fig. 1. The 2-plane coupler is an 8-port circuit, and the dimensions of the input ports are determined so that only the TE10 mode is the propagation mode. However, in the coupled region, because the width and height of the waveguide increase, higher-order modes such as TE20 and TE11 modes also become propagation modes. The function of the two-plane hybrid coupler is realized by adjusting the propagation constants and reflections of these higher-order modes and the fundamental mode.

In previous studies, the shape of the coupling region was uniform. In this study, the coupling region was divided into multiple parts and the cross-sectional shape of each region was designed by a genetic algorithm. Also, a hybrid analysis of the mode-matching method and the finite element method was used for the analysis. The right figure in Fig. 1 shows the final design with 3 steps in the coupling region. As a result, the fractional bandwidth has increased from 7.2% (21.2GHz-22.8GHz) to 9.6% (21.3GHz-23.5GHz).

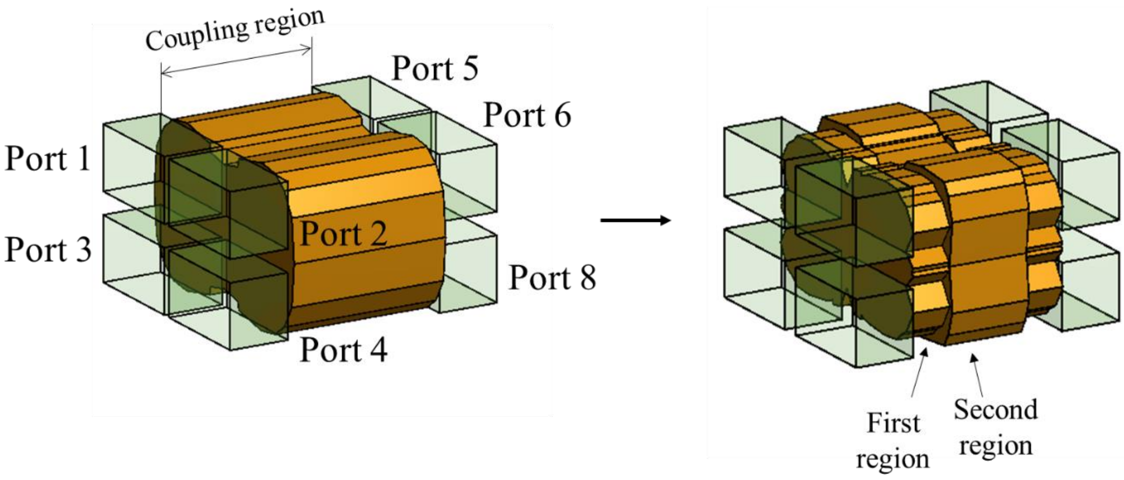


Fig1. Comparison of conventional and new model of two-plane hybrid coupler

Referrence

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

[2] Shota Yamakawa, Takashi Tomura, and Jiro Hirokawa, "Mode-matching Analysis and Genetic Algorithm Optimization for a Two-plane Coupler by Changing the Cross-sectional Shape of the Coupling Region", Proc. of International Symposium on Antennas and Propagation (ISAP), FR-IF, 220097, Oct, 2021.

Design of a Waveguide Two-plane Hybrid Coupler with Nonuniform Division

Multibeam antenna now is now being paid increasingly attention due to its potential application in 5G and sub-6G projects. As a widely applicable passive multibeam antenna feeding network system, Butler matrix is comprised of hybrid couplers, crossover junctions and phase shifters. So far, a literature [2][3] has developed a novel two-plane hollow-waveguide coupler to realize equally balanced hybrid or a cross junction among four adjacent output ports for two-dimensional multi-beam Butler matrix application. However, in 2D hollow waveguide Nolen matrix [2], two-plane nonuniform division hybrid coupler should probably be utilized, which is equivalent to cascading of two H-plane couplers and two E-plane couplers but with the advantage of length being reduced in around half. Through theoretical derivation, it can be found that for two-dimensional coupler with the same ratio in the horizontal and vertical directions, internal modes in coupled region follow consistent constraints. This paper will introduce a newly proposed 2-plane unequal division coupler.

The proposed two-plane hybrid coupler with nonuniform division $1{:}\sqrt{2}{:}\sqrt{2}{:}2$ is shown in Figure.1. The four propagating modes in the ridge waveguide coupled region include TE10-like mode, TE20-like mode, TM11-like mode and TM21-like mode. The four propagation constants $\beta_{10}, \beta_{20}, \beta_{11}$ and β_{21} should satisfy a specific relationship during operation bandwidth. The coupled region shape is derived through optimization process of mode-matching and FEM joint algorithm. The output S51, S61, S71 and S81 from 21.5GHz to 22.5GHz correspond to an incident wave from Port 1 has the deviation of the output amplitudes from the theoretical value do not exceed ±0.5dB. And phase difference among four output diverges not over ±10 degree compared with ideal results.

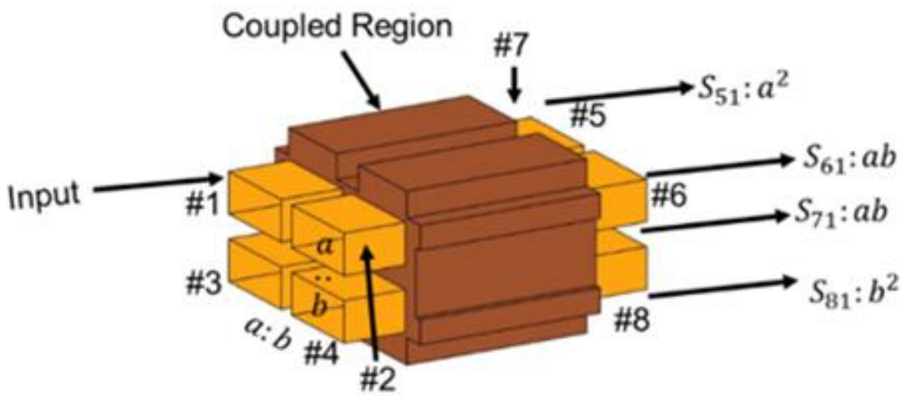


Fig. 1 One body two-plane coupler with nonuniform division

Referrence

[1] D. Kim et al. IEEE Trans. Microw. Theory Tech., vol. 64, no. 3, pp. 776-784, Mar. 2016.

[2] N.J.G. Fonseca, "Printed S-band 4×4 Nolen matrix for multiple beam antenna applications," IEEE Trans. Antennas Propag., vol. 57, no. 6, pp. 1673-1678, Jun. 2009.

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Okada Laboratory

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

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

Associate Professor Atsushi Shirane

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

Professor Hiroyuki Sakai

Specially Appointed Professor Hiroyuki Sakai received the B.S. and M.S. degrees in electrical engineering from Osaka University, Osaka, in 1984 and 1986, respectively. In 1986, he joined the Semiconductor Research Center, Matsushita Electric Industrial Co., Ltd., Osaka, and engaged in research and development of high-speed GaAs digital ICs. From 1991 to 1992, he took an active part in the development of GaAs RF ICs for very compact cellular phones. In 1993, he started to research and develop the millimeter-wave devices and its ICs. In 1995, he joined the Electronics Research Laboratory, Matsushita Electronics Corporation, Osaka, and continued his research and development on millimeter-wave devices, particularly a new millimeter-wave IC concept named millimeter-wave flip-chip IC. From 1998 to 2000, he visited Stanford University, Stanford, CA, USA, as a Visiting Scholar, expanded his research subjects to new Si-based RF devices and their integration technologies. From 2012 to 2017, he continued his research on mm-wave ICs based on GaAs, GaN, Si-BiCMOS and CMOS LSI technologies at some Laboratories of Panasonic Corporation.

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

Associate Professor Jian Pang

Special-Appointed Associate Professor Jian Pang received the bachelor's and master's degrees from Southeast University, Nanjing, China, in 2012 and 2014, respectively, and the Ph.D. degree from the Department of Physical Electronics, Tokyo Institute of Technology, Tokyo, Japan, in 2019. From 2019 to 2020, he was a Post-Doctoral Researcher with the Tokyo Institute of Technology. From 2020 to 2022, he was a Special-Appointed Assistant Professor with the Tokyo Institute of Technology.

Dr. Pang is currently a Special-Appointed Associated Professor with the Tokyo Institute of Technology, Tokyo, Japan, focusing on 5G millimeter-wave systems. His current research interests include high-data-rate low-cost millimeter-wave transceivers, power-efficient power amplifiers for 5G mobile systems, multiple-in-multiple-out (MIMO), and mixed-signal calibration systems.

Dr. Pang was a recipient of the IEEE SSCS Student Travel Grant Award in 2016, the IEEE SSCS Pre-Doctoral Achievement Award for the term 2018–2019, the Seiichi Tejima Oversea Student Research Award in 2020 and the IEEE MTT-S Japan Young Engineer Award in 2021.

Okada Laboratory

A 39-GHz CMOS Bi-Directional Doherty Phased-Array Beamformer Using Shared-LUT DPD with Inter-Element Mismatch Compensation Technique for 5G Base-Station

In 5G analog beamforming systems, due to the high PAPR of 5G OFDMA-mode modulated signals, the power efficiency is degraded at the deep power back-off (PBO) region. Doherty PA architecture can be a promising approach for PAE improvement. The digital pre-distortion (DPD) can also be applied to further mitigate the system nonlinearity. However, the single lookup table (LUT) DPD improvement with Doherty PA is limited by the PVT sensitivity of PA. To address this issue, a 39-GHz bi-directional Doherty phased-array beamformer is presented.

The block diagram of the 39-GHz phased-array beamformer and its die micrograph are shown in Fig. 1, which consists of 4 H-pol. and 4 V-pol. beamformer elements. Each element is composed of a bi-directional Doherty PA-LNA, a 3-stage bi-directional RF VGA, and an RF phase shifter. The phased-array beamformer is fabricated in a 65nm CMOS technology and packaged in WLCSP.

The conventional combined-LUT DPD captures the responses from all paths and minimizes the errors by digital-domain response combining. This work introduces an inter-element mismatch compensation technique. The Vth mismatch, gain and phase offset mismatches are detected by embedded self-test circuitry and then compensated over inter-element and inter-chip. Therefore, a shared-LUT DPD can be applied to the entire phased array. The proposed on-chip inter-element compensation system is shown in Fig. 2. Since the nonlinearity of Class-C amplifier is sensitive to Vth variation, Vth mismatch compensation is required. The Vth mismatch of the Doherty PA is detected by the Vth detector and 10b ADC and then compensated by tuning the gate bias through a digital interface. The Vth detection is conducted by squeezing the drain current, and the gate voltage of the diode-connected transistor is read out by the ADC as approximated Vth. The gain and phase offset mismatches are detected by an on-chip calibration block and compensated by tuning the VGA and phase shifter. Fig. 2 also shows the simulated Vth with different process corner cases. The measured RMS error for magnitude and phase detection are 0.78dB and 3.8°, respectively.

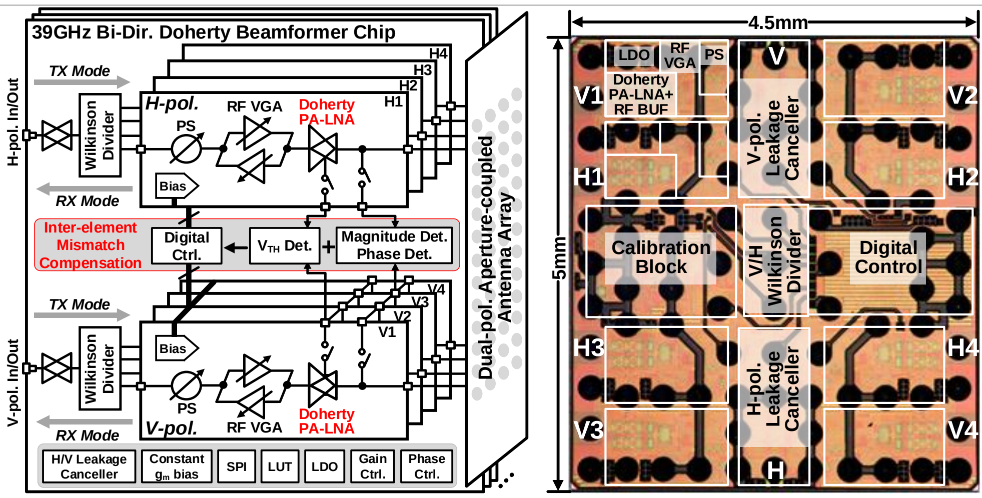


Fig. 1. Proposed 39GHz phased-array transceiver with inter-element mismatch comp. technique.

The 5G OFDMA-mode modulated signals are utilized in the following measurement. The proposed TX-mode single element achieves 10.2-dBm output power in 64QAM with −25.1-dB EVM without DPD, and the corresponding ACLR is −30.7dBc. A 256-QAM EVM of −31.6dB is also maintained with 3.9-dBm output power and −36.3-dBc ACLR. Fig. 3 shows the over-the-air (OTA) performance with shared-LUT DPD based on the 64-element phased-array module. 2 ICs located at relative distal positions are activated. The extra temperature difference is introduced between IC1 and IC2 by adding heat sink only to IC1. The DPD LUT is then extracted from IC1 and applied to both IC1 and IC2. With a fixed Pout per path, the measured EVMs with shared-LUT DPD are improved from −22.5dB to −25.0dB in 16QAM and −22.4dB to −25.0dB in 64QAM. The corresponding ACLRs are suppressed from −28.7dBc to −32.4dBc in 16QAM and −28.7dBc to −32.1dBc in 64QAM. The 64-element module achieves a 55.2-dBm saturated EIRP and also supports 21-Gb/s single-carrier data streaming. As shown in Fig. 3, the measured 64-element TX EVM is −25.2dB at 43.2 dBm in 3.5GSymbol/s 64-QAM modulation and the corresponding 64-to-4 elements TX-to-RX EVM is −22.5dB. Fig. 4 compares this work with the state-of-the-art 5G phased-array transceivers. This work compensates the inter-element mismatches for shared-LUT DPD, thus enhancing EVM and ACLR characteristics.

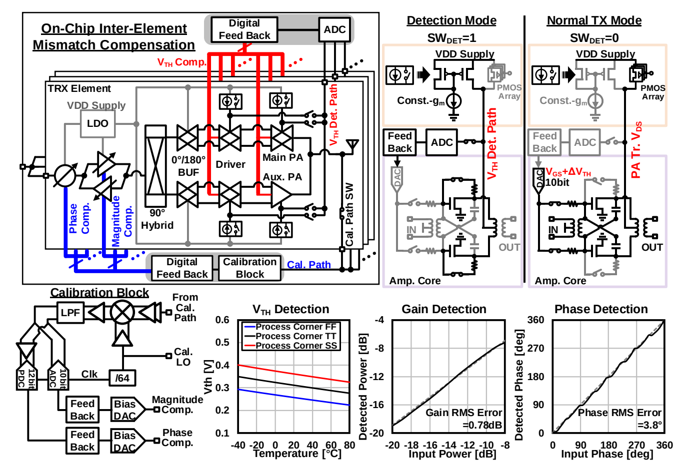
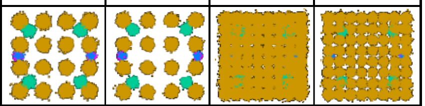


Fig. 2. Proposed mismatch comp. circuits.

Modulation	16QAM OFDMA		64QAM OFMDA	
MCS* & BW	MCS 10 / 400MHz@39GHz		MCS 19 / 400MHz@39GHz	
Pout	11.4dBm/path		11.3dBm/path	
DPD	Yes	Yes	Yes	Yes
Inter-element Mismatch Compensation	NO	Yes	NO	Yes
Constellation				
TX ACLR	-28.7dBc	-32.4dBc	-28.7dBc	-32.1dBc
TX EVM (RMS)	7.5% (-22.5dB)	5.6% (-25.0dB)	7.6% (-22.4dB)	5.6% (-25.0dB)

*5G NR MCS index table2 for PDSCH is used. (Table 5.1.3.1-2 in 3GPP TS 38.214 V15.2.0)

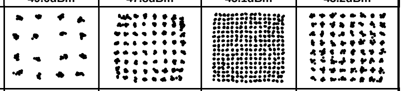
64-to-4 elements TX-to-RX Single Carrier OTA	Modulation Scheme	16QAM	64QAM	256QAM	64QAM
	Baud Rate	400MSymbol/s			3.5GSymbol/s
	TX EIRP (64 elements)	49.6dBm	47.8dBm	45.1dBm	43.2dBm
	TX Constellation				
	TX EVM (RMS)	9.1% (-20.8dB)	5.6% (-25.0dB)	2.6% (-31.6dB)	5.5% (25.2dB)
	TX-to-RX EVM (RMS)	11.8% (-18.6dB)	7.6% (-22.4dB)	3.4% (-29.4dB)	7.6% (-22.5dB)

Fig. 3. Measured constellations and EVMs.

		This work			[6] JSSC20	[7] JSSC19	[8] ISSCC20	
Process		65nm CMOS			65nm CMOS	65nm CMOS	28nm CMOS	
Freq. Band		39GHz			28GHz	39GHz	39GHz	
Beamformer Integration		Bi-directional Doherty PA-LNA, PS			PA, LNA, PS	Class-AB PA, LNA, PS	Stacked PA, LNA, PS	
TX Psat		18.9dBm			15.1dBm	15.5dBm	>16.5dBm	
TX EIRPsat		55.2dBm 64 elements			45.6dBm 32 elements	53dBm 64 elements	-	
PA Peak PAE		30.4%			20%	25.5%	-	
PA PAE @6dB PBO		17.8%			4.7%	9.5%*	-	
PDC/path		TX: 402mW@P_{sat} RX:87mW			TX:252mW @11.3dBm RX:112mW	TX:375mW RX:125mW	TX:105mW @6dBm RX:39mW	
Area/path		0.82mm²			0.58mm²	1.78mm² *	0.77mm² *	
SC-Mode	Modulation Scheme	64QAM			64QAM	-	-	
	Data Rate	21Gb/s @EIRP=43.2dBm			15Gb/s @EIRP=35.2dBm	-	-	
5G OFDMA-Mode	Modulation Scheme	64QAM			64QAM	64QAM	64QAM	
	Inter-Element Mismatch Comp.	No	No w DPD	Yes w DPD	No	No	No	
	TX Pout/path (dBm)	11.3	11.3	11.3	5.6	3.6	6	8.8
	TX EVM (dB)	-	−22.4	−25	−25	−24.6	−34	−27
	TX ACLR (dBc)	−25.4	−28.7	−32.1	−28.4	-	−36.5	-

*Estimated from paper

Fig. 4. Comparison Table.

Okada Laboratory

A Power-Efficient 24-to-71GHz CMOS Phased-Array Receiver Utilizing Harmonic-Selection Technique Supporting 36dB Inter-Band Blocker Rejection for 5G NR

This work introduces a 24.25-71GHz phased-array receiver. A harmonic-selection technique is proposed to extend the operating bandwidth with low power consumption

Fig. 5 shows the block diagram of the proposed phased-array receiver. Each of the receiver channel consists of a dual-mode multi-band LNA, a harmonic-selection mixer, a tri-phase LO generator, and a LO phase shifter. LO phase shifting architecture is adopted in this work to obtain accurate beam steering over wide frequency range, and 360° phase shifting can be covered by each channel. The IF frequency is fixed at 8GHz. A desired mixing component can be selected from the fundamental, 2nd harmonic and 3rd harmonic, and the unselected mixing components will be suppressed by this technique. Compared with the conventional method using the fundamental frequency mixing, the operating bandwidth can be extended to 24.25-71GHz with an improved inter-band blocker rejection. The required LO frequency range is also decreased substantially for a much lower power consumption. A Hartley architecture is employed to reject the blockers at image frequencies along with the LNA band-pass response. A 90°-shifted LO is used at adjacent channel, and −90° is again applied in IF PPF to realize the Hartley operation. A hybrid PPF with a detector-base calibration scheme is proposed in this work for supporting higher im-age rejection and improved CG.

Fig. 6 shows chip micrograph and Fig. 7 demonstrates the on-wafer measured characteristics. The proposed phased-array receiver supports 24.25 to 71GHz operation covering the major 5G bands. With a fixed IF frequency of 8GHz, a single-channel CG of 15dB could be realized by this work among all

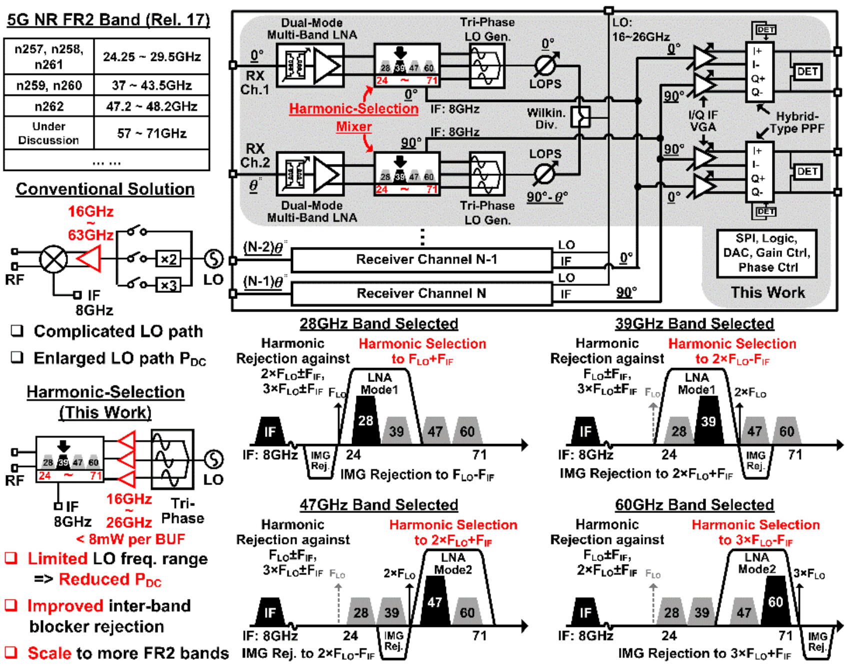


Fig. 5. Block diagram of proposed multi-band phased-array receiver.

LNA modes and harmonic-selection modes. The corresponding single-channel NFs are 4.6dB, 5.2dB, 6.1dB, and 5.8dB at 28GHz, 39GHz, 48GHz, and 61GHz, respectively. The measured IP1dB is also shown for each band. The achieved IP1dBs are -17.6dBm at 28GHz, -20.1dBm at 39GHz, -26.6dBm at 48GHz and -31.8dBm at 61GHz. The images are suppressed by the LNA band-pass characteristics and the IF PPF. The measured IRRs are always better than 52dB over all operation bands. The proposed receiver is also evaluated with 5G standard-compliant OFDMA-mode modulated signals. The measured EVMs in 64QAM are -31.6dB at 24.25GHz. -33.4dB at 28GHz, -31.9dB at 39GHz, -32.5dB at 47.2GHz, -30.5dB at 60.1GHz, and -28.9dB at 71GHz. The power consumption for a single receiver channel is 36mW, 32mW, 51mW, and 71mW at 28GHz, 39GHz, 47.2GHz, and 60.1GHz, respectively.

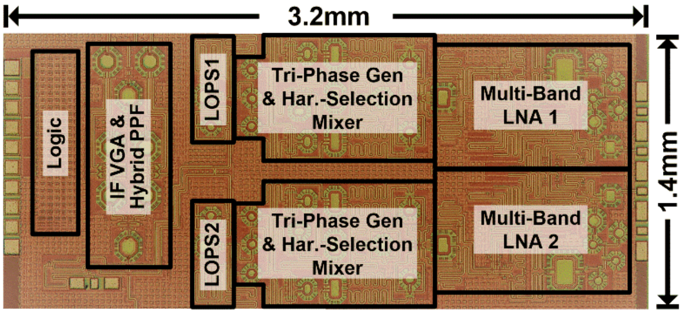
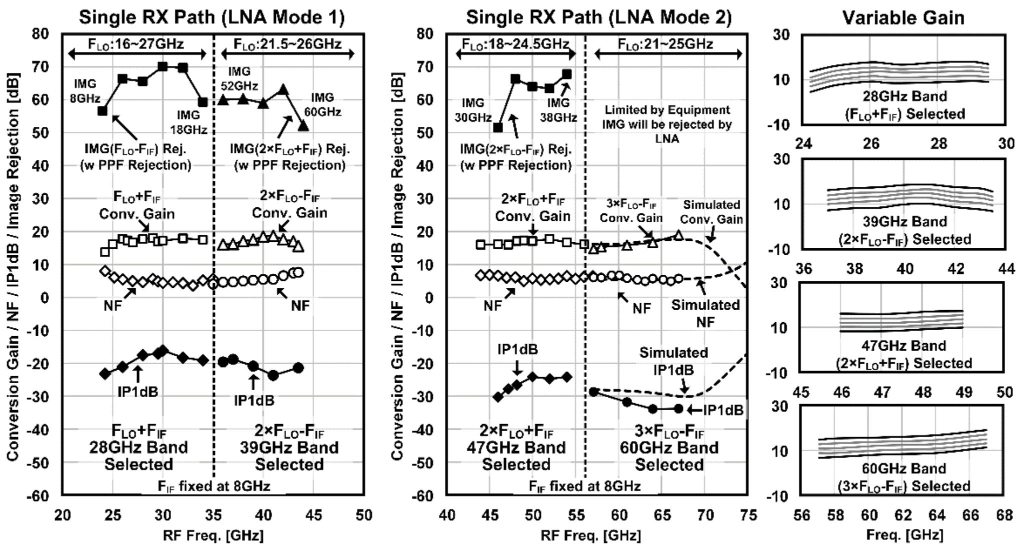
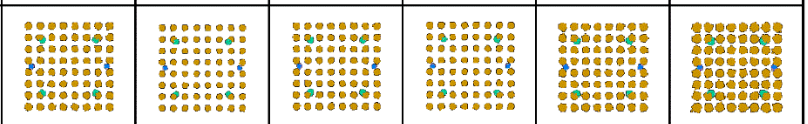


Fig. 6. Block diagram of proposed multi-band phased-array receiver.



Freq.	24.25GHz	28GHz	39GHz	47.2GHz	60GHz	71GHz
Modulation*	64QAM (MCS19)	64QAM (MCS19)	64QAM (MCS19)	64QAM (MCS19)	64QAM (MCS19)	64QAM (MCS19)
Mode	OFDMA	OFDMA	OFDMA	OFDMA	OFDMA	OFDMA
BW$_c$	400MHz	400MHz	400MHz	400MHz	400MHz	400MHz
Const.						
EVM (RMS)**	-31.6dB (2.6%)	-33.4dB (2.1%)	-31.9dB (2.5%)	-32.5dB (2.4%)	-30.5dB (3.0%)	-28.9dB (3.6%)

*5G NR MCS index table 2 for PDSCH is used. (Table 5.1.3.1-2 in 3GPP TS 38.214 V15.2.0). **Measured EVMs are referred to the RMS magnitude.

Fig. 7. Measured receiver characteristics.

Okada Laboratory

A 3.4mW/element Radiation-Hardened Ka-Band CMOS Phased-Array Receiver Utilizing Magnetic-Tuning Phase Shifter for Small Satellite Constellation

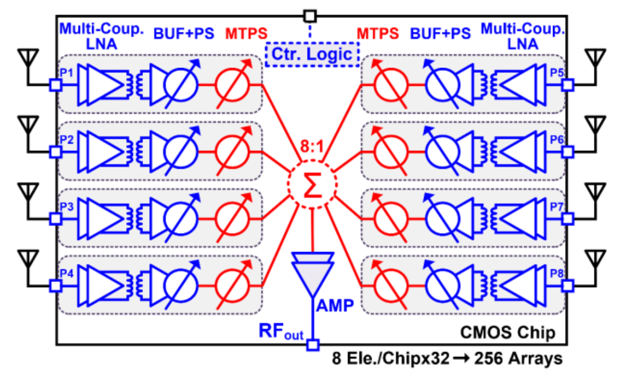


Fig. 8. System diagram of the proposed receiver.

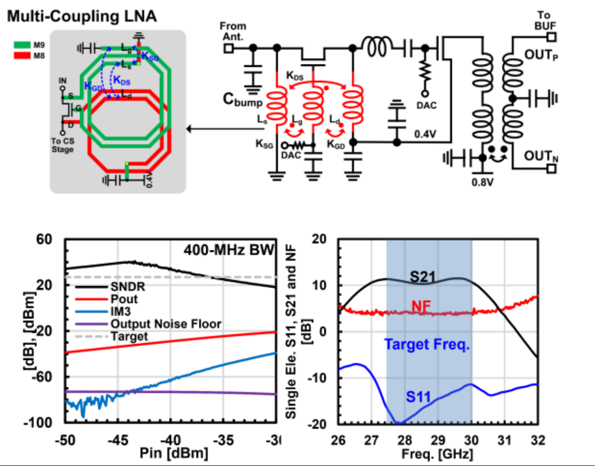


Fig. 9. Low-power LNA and measured results.

Low Earth Orbit (LEO) satellite constellation has been demonstrated as a ground-breaking technology for providing low-cost low-latency global internet access. However, each satellite needs more than 200kg launch mass due to bulky wireless components and solar cells, which raises a serious cost issue. One possible solution is further minimizing satellite mass, such as cube satellite, by realizing an ultra-low-power Ka-band phased-array transceiver. LEO satellites also need beam steering function by using a phased-array antenna, and only thin shield layer can be inserted between antennas and ICs for avoiding redundant mass and insertion loss. Thus, the radiation-harden and low power consumption are key requirements for such cube satellite phased arrays.

Fig. 8 shows the system block diagram of the proposed low-power and radiation-hardened beamforming receiver. A single-element beamformer consists of a 2-stage multi-coupling LNA, a neutralized cascade RF buffer with a built-in 180° phase shifter, and a magnetic tuning phase shifter (MTPS).

Fig. 9 illustrates the circuit schematic of the proposed multi-coupling low-power common-gate (CG) LNA and the proposed neutralized cascade buffer with a built-in 180° phase shifter. Compared with the inductor-based CG LNA, the proposed multi-coupling CG LNA dramatically decreases the source input impedance. The single-element output power and IM3 are also measured in Fig. 9. At 29GHz, the peak SNDR is 40dB. The measured single-element S11, S21, and noise figure at 29 GHz are -14dB, 11dB and 3.8dB, respectively.

Fig. 10 demonstrates the circuit schematic and the working mechanism of the proposed magnetic-tuning radiation-hardened phase shifter. In terms of the conventional vector-summing phase shifter (VSPS), the inevitable leakage current ileak1 and ileak2 causes phase shift and gain reduction, respectively. In contrast, the proposed magnetic-tuning phase shifter mitigates the leakage current impact. Due to the negligible leakage at the variable resistor region, the drain to source current after radiation is equal to the one before radiation. The measured TID degradations of the conventional and the proposed receivers are shown in

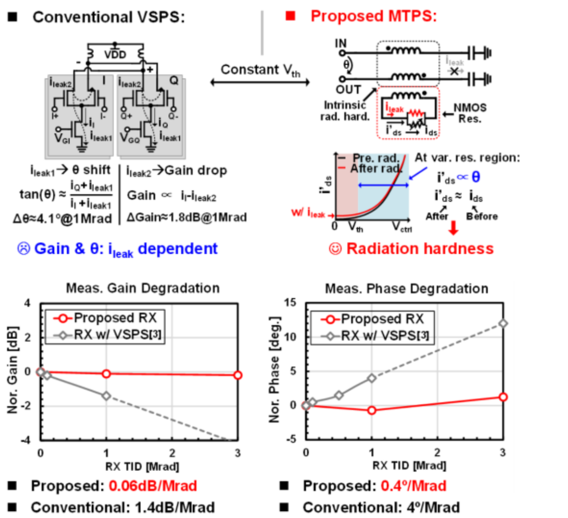
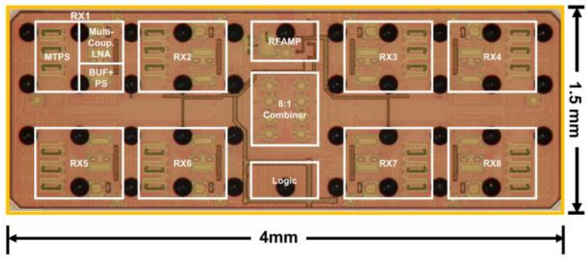


Fig. 10. Phase shifter and TID measured results.



Modulation	16 APSK	16 APSK	256 APSK	256 APSK
Symbol Rate	0.8 GBaud	1.6 GBaud	0.8 GBaud	1.6 GBaud
Constellation*				
Data Rate	3.2 Gb/s	6.4 Gb/s	6.4 Gb/s	12.8Gb/s
RX EVM (RMS)	-36.4dB	-33.1dB	-35.7dB	-33.2dB

*Measured by 8x8 Sub-Array Module

Fig. 11. Die photo and measured constellations.

Fig. 10. Compared with the conventional receiver, the proposed one achieves 0.06dB/Mrad gain and 0.4°/Mrad phase degradations at 29GHz.

Fig. 11 shows the die micrograph, the total chip area including pads is 6mm^2, where the single-element active area is 0.2mm^2. The peak OTA EVM at 29GHz is -40dB with 100MHz 16 APSK modulated signal. An OTA data rate of 12.8Gbps is achieved with 1.6GHz single carrier 256APSK modulation signal.

Fig. 12 compares this work with the state-of-the-art phased-array ICs. Utilizing the magnetic-tuning phase shifter, this work achieves the smallest RMS phase and gain errors while maintaining the 0.06dB/Mrad and 0.4°/Mrad TID gain/phase degradation, which satisfies the satellite requirements. The lowest power consumption per element is realized by employing the multi-coupling LNA and the neutralized-cascade buffer with the built-in 180° phase shifter.

	This work	Samsung RFIC2021[3]	Zhejiang Univ. ISSCC2021[4]	Samsung ISSCC20[5]	Tokyo Tech JSSC2021[1]	Anokiwave AWS-0102[8]	Anokiwave AWMF-0143[9]
Process	65nm CMOS	28nm CMOS FD-SOI	65nm CMOS	28nm CMOS	65nm CMOS	CMOS	CMOS
Application	SATCOM	5G	5G	5G	5G	SATCOM	SATCOM
Operation Band	26.7-30.4GHz	24.25-29.5GHz 37-40GHz	17.7-19.2GHz	37-40GHz	27.5-30.5GHz*	17.75-20.25GHz	26-30GHz
Integration/ chip	8xBeamformer RX	2xBeamformer RX	8xBeamformer RX	16xTRx IF,LO	8xBeamformer	8xBeamformer RX	1xBeamformer RX
Supply Voltage	0.8V	1.1V	N/A	0.9V/1.8V	1V	1.8V	1.8V
NF	3.8dB$^{\&}$	4.3-6.4dB	3.2-4.1dB	4.2-4.6	5.2dB@29GHz	3.4dB	3.5dB
Coherent Gain	23dB	32dB^ 2xElement	28dB^ 8xElement	16-59dB 16xElement	25-27dB 4xElement	22dB 8xElement	24dB 1xElement
IIP3	-22dBm$^{\&}$	-37.8dBm^	-17.4dBm*	N/A	-20dBm*	-35dBm	-16dBm
P_{DC}/Element	**3.4mW$^{\&}$**	17.3mW$^{\&}$	74mW$^{\#}$	39mW	61mW$^{\&}$	38mW$^{\&}$	195mW$^{\&}$
Area/Element	0.196mm$^{2\&}$	0.46mm$^{2\&}$	1.6mm^2	0.94mm^2	0.48mm^2	6.1mm^{2**}	3.1mm^{2**}
Array Size	256	N/A	8	16	64	N/A	N/A
Modulation	256APSK (1.6GHz)	64QAM OFDM (400MHz)	N/A	64QAM OFDM (800MHz)	256QAM OFDM (400MHz)	N/A	N/A
EVM	-33.2dB	-33.1dB	N/A	-34.8dB	-29dB*	N/A	N/A
RMS Gain Error	**0.14dB**@29GHz$^{\$}$	0.9dB	0.22dB	0.33dB	0.25dB@29GHz*	0.3dB	0.5dB
RMS Phase Error	**0.09°**@29GHz$^{\$}$	6°	1.5°	3.3°	1.4°@29GHz*	5°	3°
Temperature Gain & Phase Variation	0.03dB/°C & 0.13°/°C(-40～125°C)	N/A	0.01dB/°C & 0.06°/°C(-15°C～85°C)	N/A	N/A	N/A	N/A
TID Gain & Phase Degradation	**0.06dB**/Mrad & **0.4°**/Mrad	N/A	N/A	N/A	N/A	N/A	N/A

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

Fig. 12. Performance comparison with state-of-the-art works.

Fukawa Laboratory

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

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Our Research Interests

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

Research Topics in Recent Five Years

Transmission System

MIMO detection & CSI estimation

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

MIMO-OFDM system optimization

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

Super high rate mobile communications

- 8×16 MIMO multi-Gbps systems

Multiple Access

Collision detection

Interference mitigation

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

Access scheme

- IDMA with iterative detection
- Random packet collision solution

Wireless Security

Random phases based physical layer security

Millimeter Wave Communications

Phase noise compensation

I/Q imbalance compensation

Real zero coherent detection

Others

Constant Amplitude OFDM

Machine Learning Schemes for Wireless Communications

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

Fukawa Laboratory

Joint Transmit Power and Beamforming Control by Unsupervised Machine Learning for MIMO Small Cell Networks [12], [16]

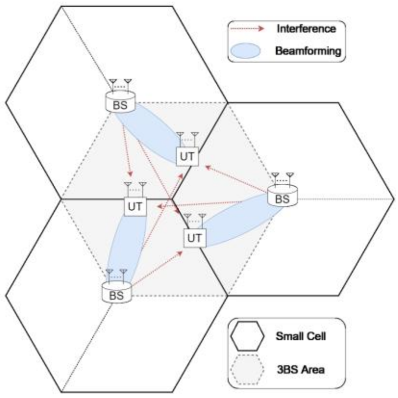


Fig. 1. The 3-BS system model.

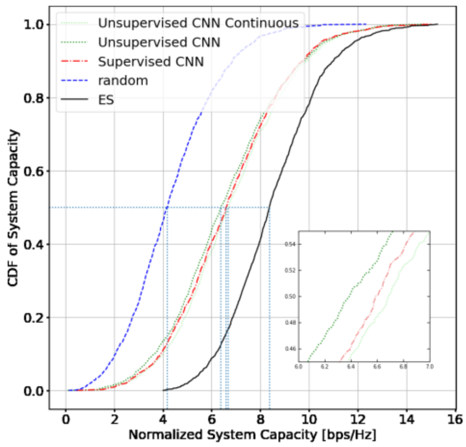


Fig. 3. CDF of system capacities.

In the fifth-generation (5G) network, densely deployed small cells are effective in improving the system capacity. However, several overlapping cells cause inter-cell interference (ICI), and degrades the system capacity. To reduce an amount of ICI, ICI coordination (ICIC) schemes for base stations (BSs) control both transmit power levels and beamforming vectors. As a conventional control scheme, the exhaustive search (ES) searches for the transmit power levels and beamforming vectors that can maximize the system capacity, but requires a prohibitive amount of computational complexity that grows exponentially with the number of BSs. To drastically reduce such complexity, this research applies a convolutional neural network (CNN) into the joint control of the transmit power levels and beamforming vectors for multiple-input multiple-output (MIMO) small cell networks. Unsupervised learning, which does not need any training data, is employed for the CNN because the application of unsupervised learning can reduce the complexity more drastically than that of supervised learning, which needs training data provided by ES.

Let us consider a cellular system with regular hexagonal small cells adjacent to each other, in which each BS is located at the center of the cell. Each cell is divided into three sectors with central angles of 120 degrees. As shown in Fig. 1, the service area is defined as the regular hexagonal area surrounded by the three BSs. UTs are randomly distributed within the service area. Each UT is supposed to communicate with the BS that provides the largest received power for the UT. The other connections are regarded as interference. The channel state information (CSI) of all BSs is assumed to be shared through the backhaul. Perfect time and frequency synchronization between the BSs and the UTs is also assumed. This research employs CNN to solve the above problem. The CNN is composed of two parts; the first part is the convolutional (CL) layer, while the second part is the fully connected (FC) layer. The overall structure of the proposed scheme is shown in Fig. 2. Note that CNN can be applied to wireless communications, owing to its feature extraction ability.

The cumulative distribution functions (CDFs) of the system capacity are shown in Fig. 3. At the

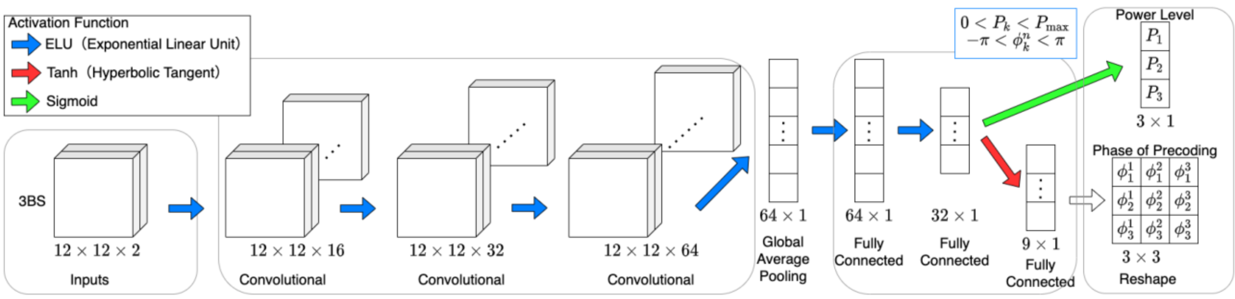


Fig. 2. The structure of CNN.

Table I.

System capacities and running times

ES	8.37 bps/Hz	14,628 s	
Supervised learning	6.59 bps/Hz	7,890 s	Offline
		2.01 s	Online
Unsupervised learning	6.39 bps/Hz	6,628 s	Offline
		0.77 s	Online
Random	4.17 bps/Hz		

CDF of 0.5, the unsupervised learning without any training data can achieve almost the same performance as that of the supervised learning with a lot of training data. Table I shows the running time of the proposed and conventional schemes, besides the system capacity at the CDF of 0.5. Here, "Online" and "Offline" correspond to the prediction and training of the CNN, respectively. The online process and ES used 1,600 test datasets, while the offline process used 16,000 training datasets. It can be seen that the unsupervised learning can reduce the complexity more drastically than the supervised learning, while achieving almost the same system capacity. Although ES can maximize the system capacity, it requires a much larger amount of computational complexity than the other schemes.

Multiuser Detection of Collided AIS Packets with Accurate Estimates of Doppler Frequencies [3], [6], [9], [15], [18]

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

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

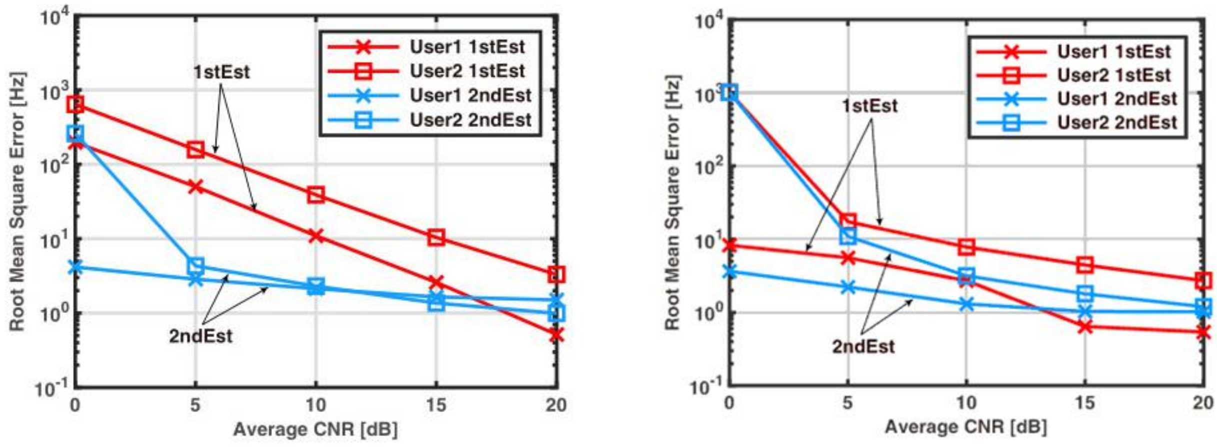
Algorithm 1. Quasi-Newton method

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

The proposed quasi-Newton method employs Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithm as the optimization scheme. This scheme can reduce an amount of computational complexity to calculate the inverse Hessian, because BFGS algorithm can approximate the inverse Hessian.

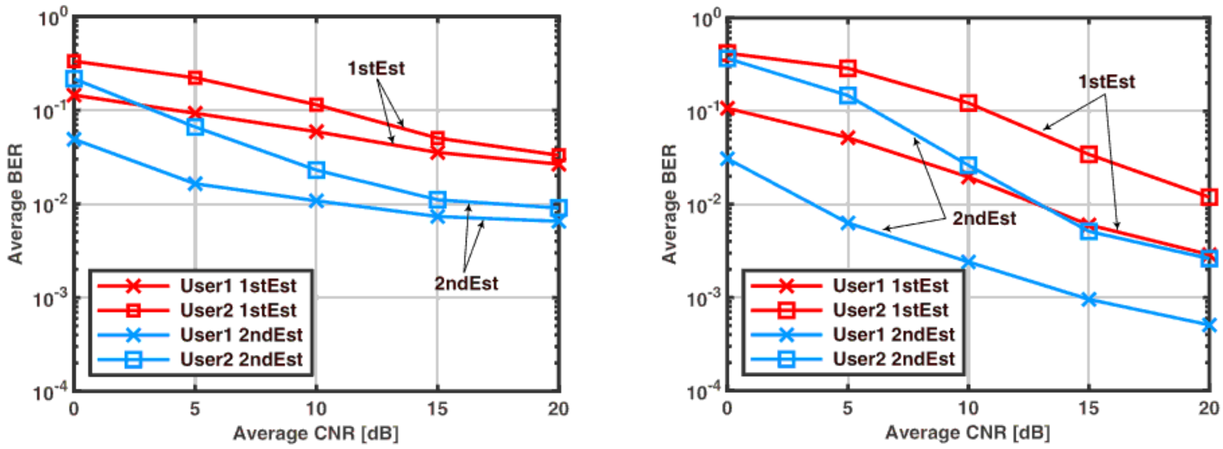
Furthermore, the quasi-Newton method is super-linearly convergent and thus requires fewer iterations for convergence. Algorithm 1 lists the procedure of the quasi-Newton method, in which l is the index of iterations, $MaxIterations$ is the maximum number of iterations, $\hat{\mathbf{f}}_{d\ \mathrm{CD}}$ is the estimate of $\mathbf{f}_d$ by CD and set to the initial value, $\mathbf{H}_l$ denotes the approximated inverse of Hessian, α is the step size, $\nabla \mathrm{PM}(\mathbf{f}_{dl})$ is an approximated gradient of PM with respect to $\mathbf{f}_{dl}$, and $\mathbf{I}$ is the identity matrix.

The estimation error of the Doppler frequencies was evaluated as the root mean square error (RMSE). Figs. 4(a) and (b) show the RMSE when desired to undesired signal power ratio (DUR) was set to 6 dB and 10 dB, respectively. In addition, "1stEst" and "2ndEst" indicate the RMSEs of the initial (first) estimation using CD and the updated (second) estimation using the proposed scheme, respectively. It can be seen from the figures that the quasi-Newton method can improve the accuracy of the Doppler frequency estimation, except that RMSE of 2ndEst of user 1 is a little worse than RMSE of 1stEst of user 1 when the average CNR is greater than 15 dB. Figs. 5(a) and (b) show the average BER performance when DUR was set to 6 dB and 10 dB, respectively. It is seen that the proposed scheme can improve the BER performance more drastically than the initial parameter estimation using CD. In particular, the average BER of user 1 can achieve 1×10^{-2} when DUR is 6 dB and the average CNR is 10 dB.



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

Fig. 4. RMSE of Doppler frequency



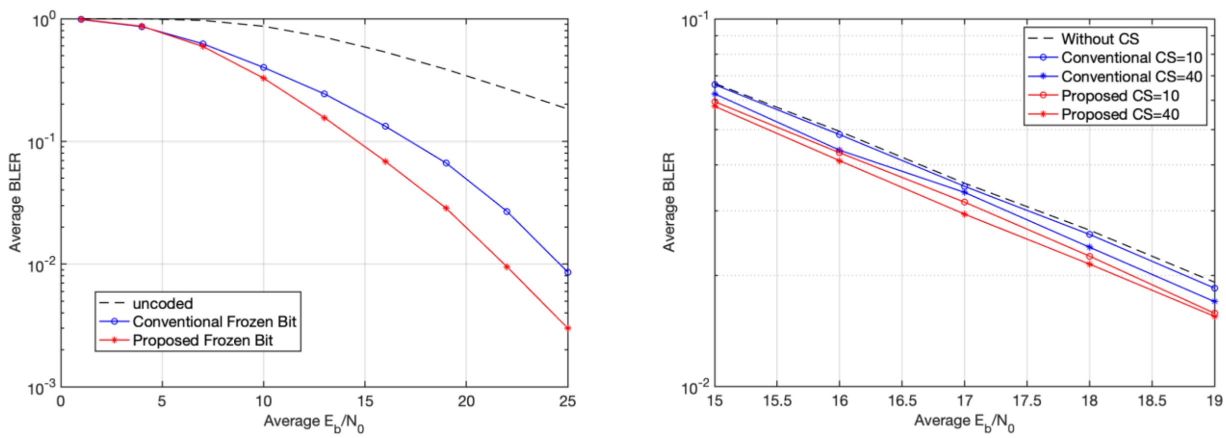
(a) DUR 6 dB (b) DUR 10 dB

Fig. 5. Average BER

Encoding and Decoding of Polar Codes for Frequency Selective Fading Channels [13], [17]

The polar code has attracted much attention because it has been adopted as the coding scheme for control channels of the fifth-generation mobile communications (5G) and beyond. In the encoding process, some information bits that are likely to be incorrectly decoded are selected as the frozen bits and fixed to a certain value. Almost all conventional schemes carry out this selection on the assumption of the additive white Gaussian noise (AWGN) channel. To improve the decoding performance, a conventional belief propagation (BP) decoder bit-flips some decoded bits belonging to the critical set (CS) that is a set of indices of which information bits are not the frozen bits but tend to be incorrectly decoded. However, the combination of these conventional encoding and decoding schemes may incur degradation of block error rate (BLER) over frequency selective fading channels, because channel state information (CSI) is not considered at all. To alleviate the BLER degradation, this research proposes a joint encoding and decoding scheme of the polar code that take into account CSI on orthogonal frequency-division multiplexing (OFDM) transmission. Firstly, the BP decoder of the proposed scheme calculates likelihood ratios (LRs) of the information bits from LRs of the received sequence, on the basis of the CSI during the estimation period. Secondly, some information bits are assigned to the frozen bits on the criterion of the absolute values of their log LRs (LLRs). Information on the frozen bits is fed back to the encoder. Thirdly, some information bits excluding the frozen bits are assigned to CS on the same criterion during the decoding period. Finally, the bits belonging to CS are bit-flipped in ascending order of reliability.

Computer simulations are conducted. The average BLERs of the conventional and proposed frozen-bit schemes are shown in Fig. 6(a). It can be seen that the average BLER of the proposed frozen-bit scheme outperforms that of the conventional one, which assigns the frozen bits on the assumption of not a real channel but the AWGN channel. Specifically, the proposed assignment can achieve average E_b/N_0 gain of 3 dB over the conventional one at the same average BLER, when the average E_b/N_0 is greater than 15 dB. The average BLERs of the conventional and proposed CS assignment are shown in Fig. 6(b). It can be seen that the proposed CS assignment outperforms the conventional CS with less flipping times. Specifically, the proposed CS with 10-bit flipping achieves better BLER performance than the conventional CS with 40-bit flipping, which means that the proposed CS scheme can reduce an amount of computational complexity for bit flipping with the conventional one by 75%.



(a) Frozen Bit **(b) Critical Set**

Fig. 6. BLER Performances

Fujii and Omote Laboratory

Specially Appointed Professor Teruya Fujii

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

Specially Appointed Associate Professor Hideki Omote

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

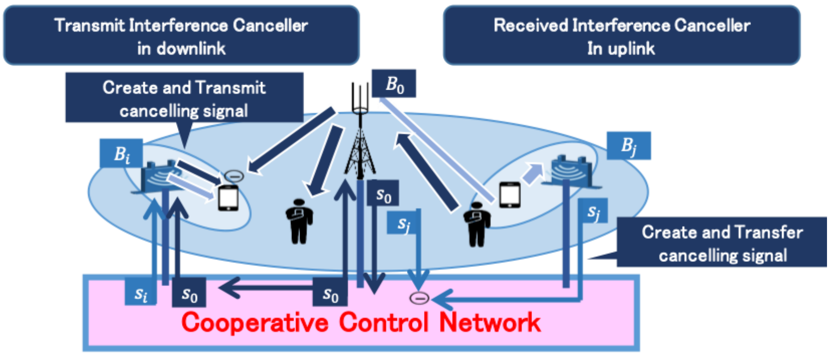
Recent Research Topics

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

A Study on Transmit and Receive Interference Canceller for 3D Layered Cell Construction in Broadband Mobile Communication [1]~[4][7][9][12]

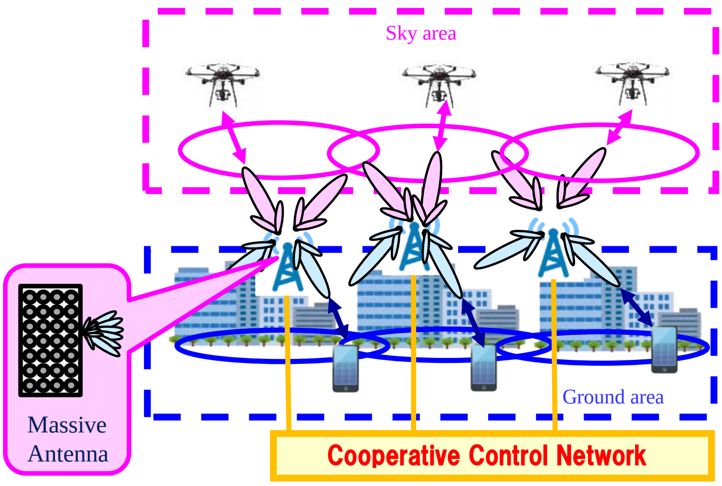
In the three-dimensional(3D) layered cell construction in same frequency bands are used in both macro and small cells, we pioneered interference cancellation technology using "cooperation control network" where each cell cooperates through a network ahead, for LTE and 5th generation mobile communications.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

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



A Study on Frequency Sharing in 3D Cell Structure consisting of Ground and Sky Cells by using Beamforming [1][3][8][13][14][17]

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



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