Mobile Communications Research Group
Tokyo Institute of Technology

2016

ANNUAL REPORT

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Tokyo Institute of Technology

Overview

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 Institute of Technology 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

Institute Library

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.

http://www.titech.ac.jp/

Mobile Communication Research Group

Mobile Communications Research Group (MCRG) of Tokyo Institute of Technology was established in 2001. The objective of the group is to conduct advanced research related to mobile communications.

Main Laboratories of MCRG:

1. Propagation and Antenna Laboratory
   (Prof. Jun-ichi Takada, Assit. Assist. Prof. Kentaro Saito, Assist. Prof. Takuichi Hirano)

2. System Laboratory
   (Prof. Kei Sakaguchi, Assistant Prof. Gia Khanh Tran, Emeritus Prof. Kiyomichi Araki)

3. Signal Processing Laboratory
   (Prof. Kazuhiko Fukawa, Assist. Prof. Yuyuan Chang)

Our group conducts comprehensive research on the development of mobile communication systems covering a wide range of cutting edge technologies in the fields of the antenna and propagation, transmission systems, hardware development and signal processing. The synergy in the group creates an ideal environment for cross-disciplinary discussions and tapping of expertise resulting in various notable joint projects and developments. Our group has a weekly seminar to share the latest research outcomes among internal laboratories and to gain insight on our research activities by inviting guest speakers.

An Open House is yearly organized 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 academia and industry are invited to give key note speeches and lectures to contribute their views and visions for the future development of research in mobile communications.

http://www.mcrg.ee.mobile.titech.ac.jp/

Laboratory Introduction
&
Annual Report 2016

SAKAGUCHI LABORATORY

Professor Kei Sakaguchi

Prof. Kei Sakaguchi received the M.E. degree in Information Processing from Tokyo Institute Technology in 1998, and the Ph.D. degree in Electrical & Electronics Engineering from Tokyo Institute Technology in 2006. Currently, he is working at Tokyo Institute of Technology in Japan as a Professor and at the same time he is a Senior Scientist at Fraunhofer HHI in Germany. He received the Outstanding Paper Awards from SDR Forum and IEICE in 2004 and 2005 respectively, and three Best Paper Awards from IEICE communication society in 2012, 2013, and 2015. He also received the Tutorial Paper Award from IEICE communication society in 2006. He served as a TPC co-chair in the IEEE 5G Summit in 2016, a General co-chair in the IEEE WDN-5G in 2017, and a Industrial Workshop co-chair in the IEEE Globecom in 2017. His current research interests are in 5G cellular networks, millimeter-wave communications, and wireless energy transmission. He is a member of IEICE and IEEE.

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Assistant Professor Gia Khanh Tran

Assist. Prof. 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. 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

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

Doctor course students:

Tao Yu, Hidekazu Shimodaira

Working doctor student:

Maki Arai

Master course students:

Ryota Kosaka, Sayako Haze, Naofumi Abe, Ryosuke Kuniyoshi, Hiroaki Ogawa, Hiroaki Nishiuchi

Bachelor course student:

Moto Maruyama

Researcher:

Masahiro Suneya

Postdoc Researcher:

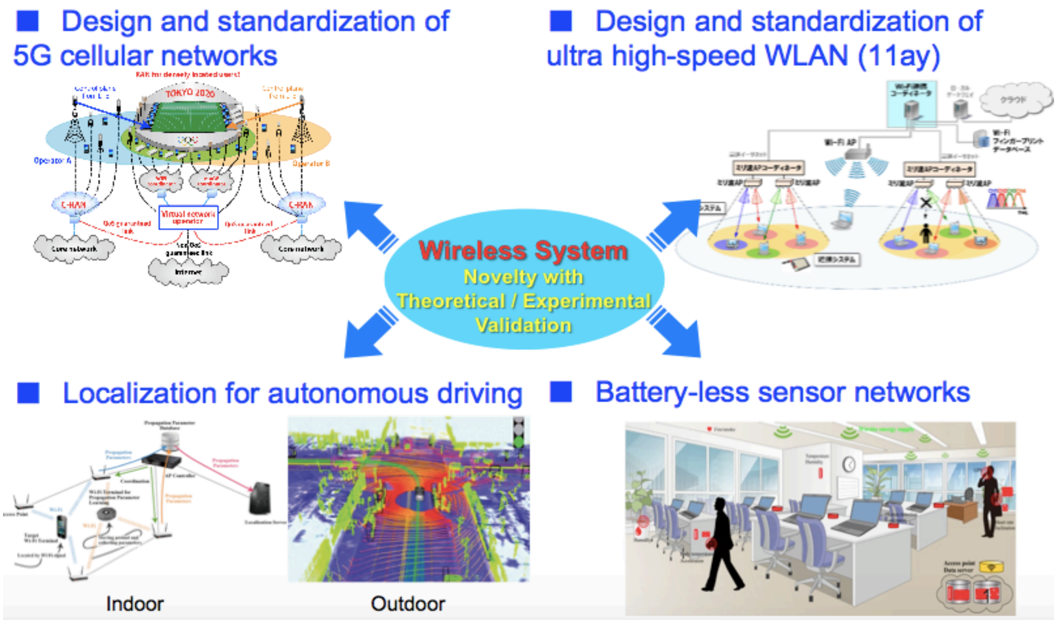
Tetsuki Taniguchi

Research Student:

Dora Ganteil

SAKAGUCHI LABORATORY

Research Interests



Sakaguchi laboratory (originally Araki-Sakaguchi laboratory) has been researching in wireless technology, since 1995. Founded on wireless communication systems, the lab has been extended widely from theoretical analysis to hardware implementation, measurement system construction and empirical experiments and from domestic to international research collaboration. Moreover, not only academic works within the university, but also co-works with various famous industrial domestic/international companies have been conducted for developing new wireless applications and contributing to the next generation wireless system standards. In the future, the laboratory will especially dedicate to researches on 5G cellular networks and IoT based tactile Internet including localization for indoor/outdoor autonomous driving and wireless power transmission.

Recent Research Topics

- **5G cellular networks**
  - PoC of mmWave Integrated Heterogeneous Networks for 5G P.7
  - mmWave Meshed Backhaul Network P.8
  - Hybrid Beamforming for mmWave Massive MIMO P.9
  - mmWave Edge Cloud (5G-MiEdge) P.10
- **Tactile Internet**
  - COI Testbed P.11
  - LED Control System using Battery-less Sensors P.12
  - Indoor Localization for Healthcare Application P.13

www.Sakaguchi-Lab.net

PoC of mmWave Integrated Heterogeneous Networks for 5G [6] [10] [13] [15] [16] [17] [22]

The world first prototype hardware as a Proof-of-Concept (PoC) of mmWave integrated Heterogeneous Networks (HetNet) for 5G has been developed through MiWEBA project with nine international collaboration partners [6]. The concept of mmWave integrated HetNet is shown in Fig. 1, where many numbers of mmWave small cells are overlaid on the current macro cell.

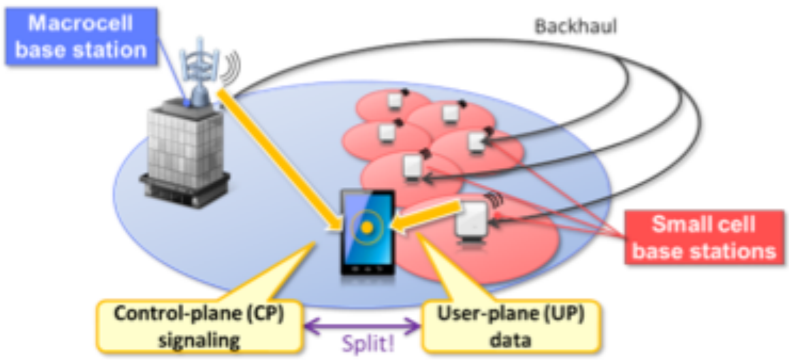


Figure 1: Concept of mmWave integrated HetNet.

A novel system architecture of Control-plane (CP) / User-plane (UP) splitting is introduced, where mmWave small cells transfer the UP with ultra-high data rate while the macro cell maintains the CP to perform mobility management of all users to realize centralized radio resource management.

The PoC hardware for the mmWave integrated HetNet is comprised of an LTE eNB as the macro cell and WiGig APs as the mmWave small cells. Figure 2 describes overall system architecture of the PoC, and corresponding photo is shown in Fig. 3. The developed UE supports dual connectivity using 2 GHz LTE and 60 GHz WiGig accesses, while the CP is stuck with 2 GHz LTE and the LTE eNB manages the UP data switching between the LTE and WiGig. The PoC hardware includes both the backhaul and access using 60 GHz band. IP-based wireless backhaul linking was established using a passive reflect array antenna, while adaptive beamforming antenna with lens was used to support access for mobile users.

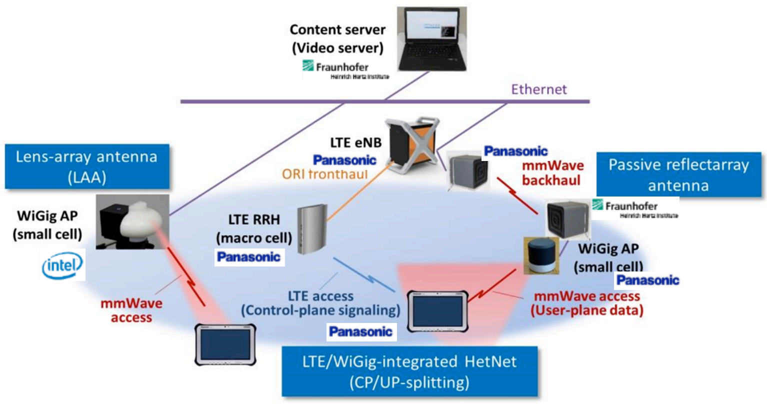


Figure 2: System Architecture of PoC.

One typical application on this PoC is "Context Aware Caching". In the demo, the client runs a video streaming application while on the move. A context aware cache entity, lying as a middle layer between the video application and the network connection, performs the data requests, using the connectivity status (mmWave connection available or unavailable) as context information. When within the coverage of an mmWave small cell, the cache pre-fetches and stores the video file chunks locally at the maximum achievable rate of more than 2.5 Gbps.

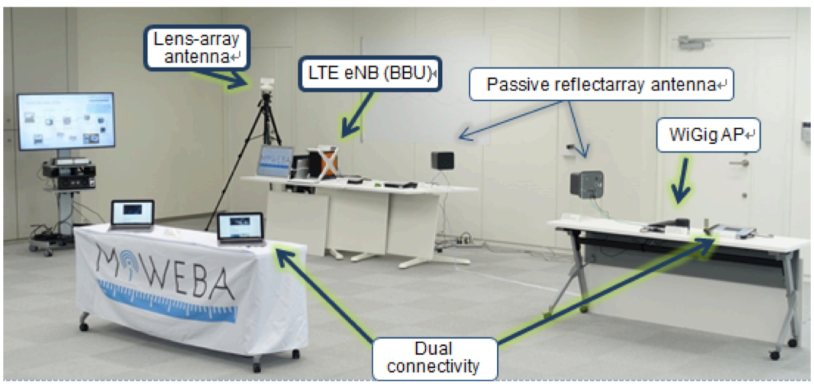
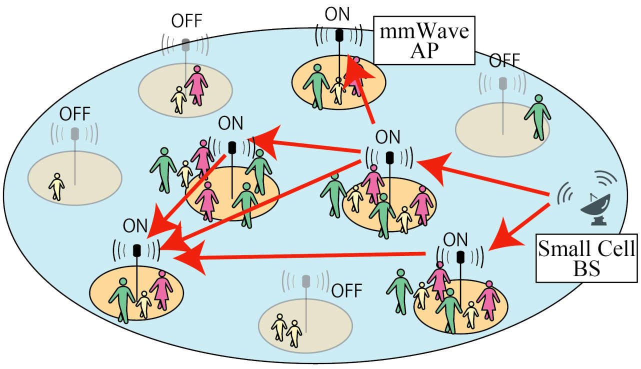


Figure 3: Photo of PoC.

mmWave Meshed Backhaul Networks[22][30]

Introduction

In order to realize the mmWave edge cloud system, it is crucial to control wireless mmWave backhaul between “Small Cell BS” and “mmWave AP” shown in Fig. 1 in the previous page. As practical user distribution is time-variant and spatially non-uniform, wireless mmWave backhaul should be controlled adaptively in accordance with such user distribution. mmWave meshed backhaul networks shown in Fig. 1 enable adaptive control of relay routes.



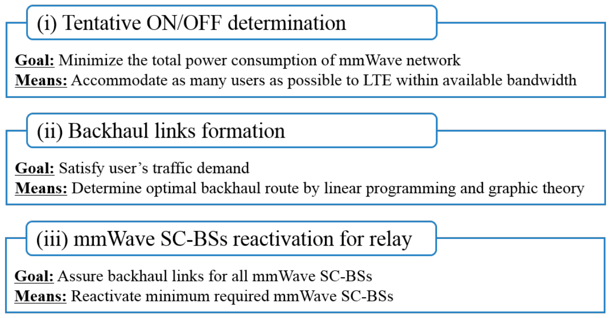


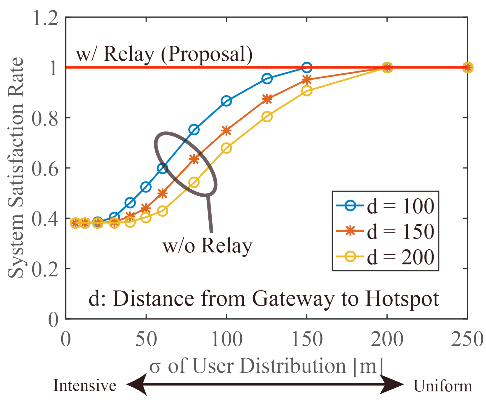
Fig.1: mmWave meshed backhaul networks **Fig.2: Algorithm flow**

Proposed Control Algorithm

Our algorithm is featured by two functionalities considering the property of user distribution. One is backhauling route multiplexing, i.e. concentration of radio backhaul resources for overloaded APs. The other is adaptive switching of mmWave APs’ ON/OFF status for underloaded APs. In order to realize these functionalities, we have to derive the best combination of backhaul links and mmWave APs’ ON/OFF status. However, there are too many combinations, thus our algorithm finds a heuristic solution through the steps shown in Fig 2.

Simulation Analysis

The performance of proposed algorithm is evaluated in terms of system satisfaction ratio shown in Fig. 3 and network power consumption shown in Fig.4. Numerical results show that the proposed algorithm can cope with locally intensive traffic, and can reduce energy consumption.



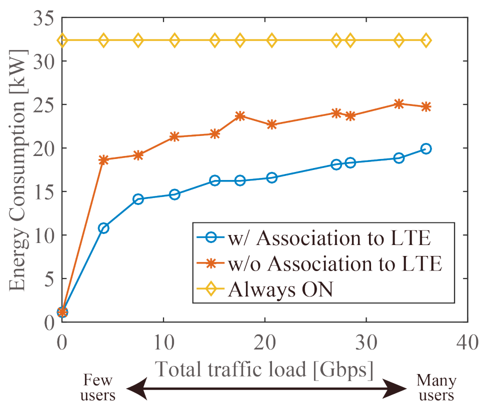


Fig.3: System satisfaction ratio **Fig.4: Network power consumption**

Hybrid Beamforming for mmWave Massive MIMO[24][32]

Recently due to the increasing of data traffic, millimeter wave (mm-Wave) band has been considered because of its license-free and wide bandwidth for the fifth generation (5G) mobile network. However large path loss is a critical problem when using mm-Wave. To compensate for the large pathloss, massive MIMO antenna as the base station antenna is a useful technology for the next generation cellar network. Massive MIMO antenna is equipped with large number of elements and so it is possible to form accurate beams and high antenna directivity. As a result, the burden at user terminal side can be reduced.

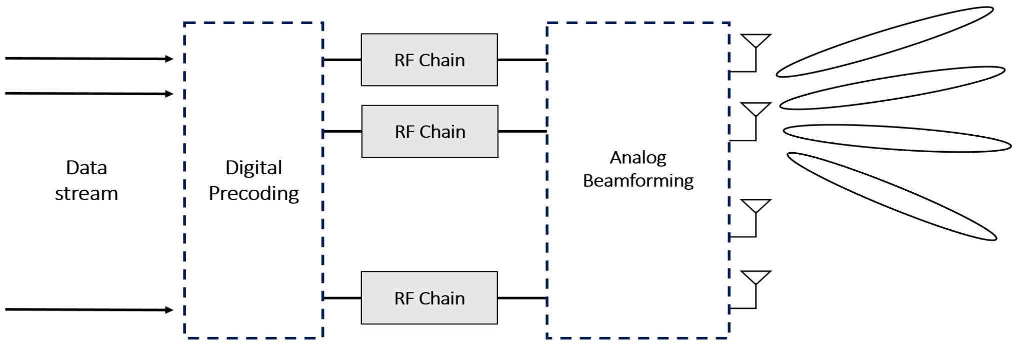


Fig. 1. Hybrid beamforming structure

However, the technique has a problem of expensive design cost and large amount of signal processing due to the large number of antenna elements. And so, hybrid beamforming is a useful technology for the realization of massive MIMO. Hybrid beamforming is a technology that includes both analog beam forming at RF and MIMO processing (digital precoding) at baseband.

To reduce calculation cost of signal processing at baseband, analog beamforming at RF should consider the interferences between users. So we propose the method of analog weight decision that direct null beam to other users. Owing to the proposed analog beamforming scheme, it is possible to remove the user interferences and reduce the burden of signal processing at baseband.

As a comparison beamforming method, we select a conjugate beamforming (CBF). CBF is to direct main beam to each user without considering user interferences. For both proposed beamforming and CBF, the residual interference components from other users are removed at baseband digital precoding. We adopt zero-forcing (ZF) as the method of digital precoding. By using the proposed algorithm, system rate has increased more than 20 percent after hybrid beamforming as well as after only analog beamforming as shown in Fig. 2 and Fig. 3 respectively.

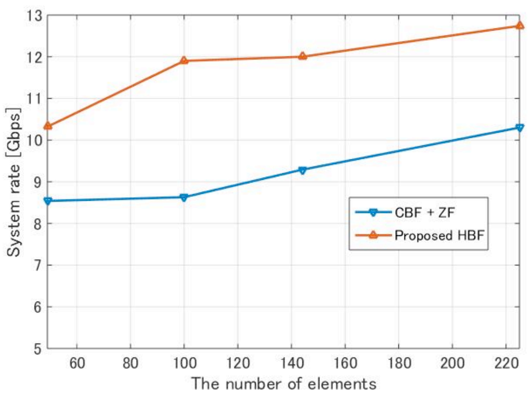


Fig. 2. System rate after hybrid beamforming

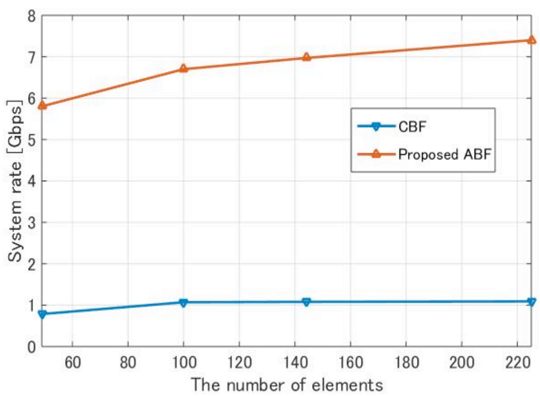


Fig. 3. System rate after analog beamforming

mmWave Edge Cloud System for 5G (5G-MiEdge) Project[18][17][21][22][23][27]

Introduction - What's 5G-MiEdge ?

In future wireless systems, e.g. 5G & beyond, realization of low latency under restricted backhauling constraints are key problems. As a solution, this research project attempts to establish a new concept based on the combination of ultra-broadband mmWave communications and mobile edge computing (MEC). This project on 5G cellular networks employing mmWave edge clouds is under the collaborative research between Japan and Europe.

Concept of mmWave Edge Cloud System

Fig.1 shows the system architecture. Small cell base station (BS) is equipped with an edge cloud server with storage and computation resources, that enables traffic mitigation in the wired backhaul and low latency necessary in mission-critical applications such as self-driving cars and virtual reality, by prefetching/cashing of data transmitted through high speed wireless mmWave backhaul.

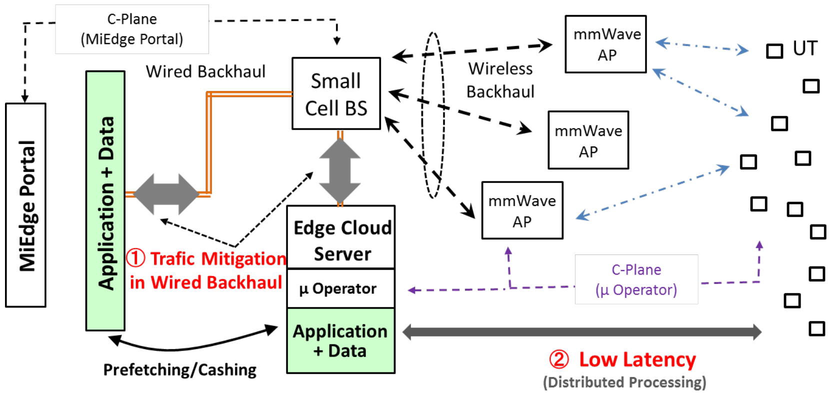


Fig. 1 mmWave edge cloud based 5G cellular system architecture

Analysis of mmWave Edge Cloud System Using A Practical Model

To evaluate the effect of the edge cloud, numerical simulations are carried out by using a new cellular model adopting moving user scenario, utilizing Winner II based geometrical stochastic channel generator 'Quadriga', developed by Fraunhofer, HHI, Germany. This model adopts mmWave heterogeneous network (HetNet) (Fig.2) in which several small cells (hotspots) supported by a micro BS equipped with the edge cloud are distributed over a legacy macro cell.

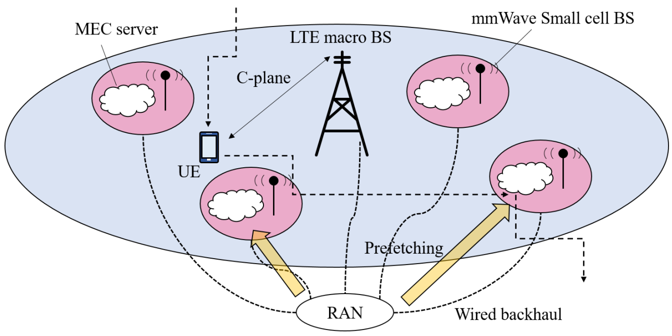


Fig.2 Overview of mmWave HetNet with edge cloud

COI Testbed[1][39]

COI (Centre of Innovation Science and Technology based Radical Innovation and Entrepreneurship Program) is a national program to continually support highly challenging researches. In this program, Tokyo Institute of Technology is assigned as a core institute of "Happiness Co-creation Society through the program of "Ishin-Denshin Intelligent Communication". Our laboratory attends this project to establish wireless sensor networks including wireless power supplying technologies.

Wireless sensor networks (WSNs) are expected to be employed for many kinds of applications. We have been focusing on power supply problem of sensor nodes, localization system and LED light control system, and we are considering to use these technologies in wide range of fields such as self-care and indoor-autonomous driving robot. We will employ the COI testbed for conducting validation experiments of the proposed system.

Fig. 1 WSNs in COI testbed

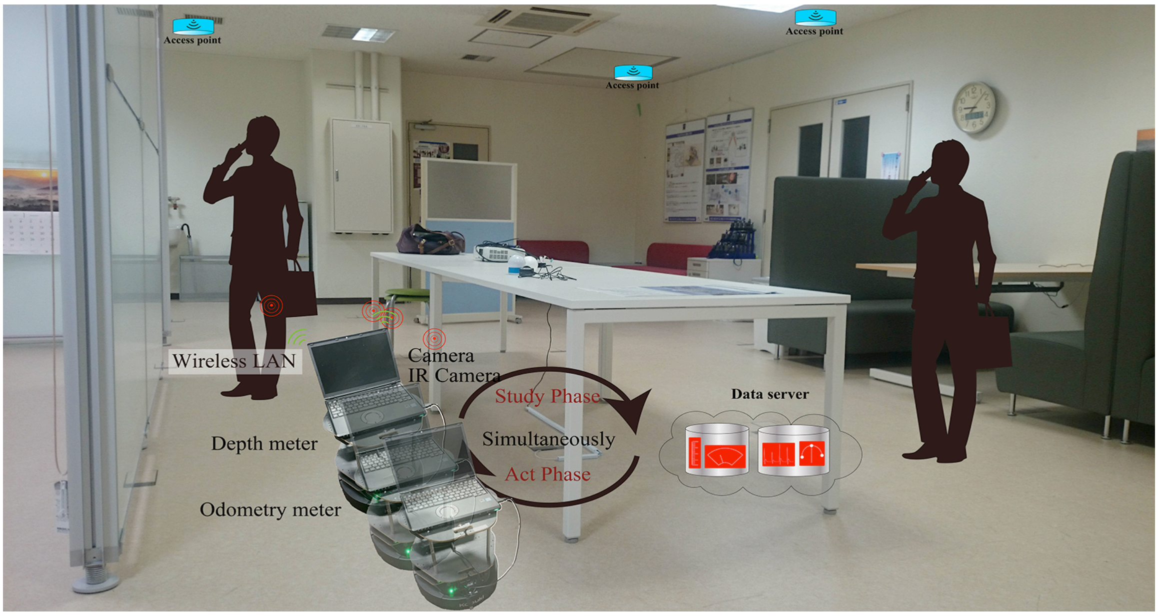


Fig. 2 WSNs application – Autonomous Robot

SAKAGUCHI LABORATORY

LED lighting Control System using Battery-less Sensors[1]

In Japan, annual lighting energy consumption accounts for 16% of national energy consumption. As an application of WSNs, this research focuses on an LED light control system based on user's occupancy and environment luminance level. Owing to the wireless energy transmission system developed by our lab, multiple sensors can be freely deployed, compared to conventional systems in which sensors have to co-locate with LED lights on the ceiling due to their power source. By using sensing data from the multiple battery-less IR sensors with overlapped coverage, user's location and motion is tracked by a maximum likelihood algorithm. The light control scheme mainly focuses on reducing office's lighting energy consumption and satisfying user's luminance requirement. The sensing data is collected by the BEMS server and the system is employed to reduce the consumed power of LED lights. The results show that this LED light control system reduces the energy consumption significantly by 57%, compared to batch control scheme, and satisfies user's luminance requirement with 100% probability.

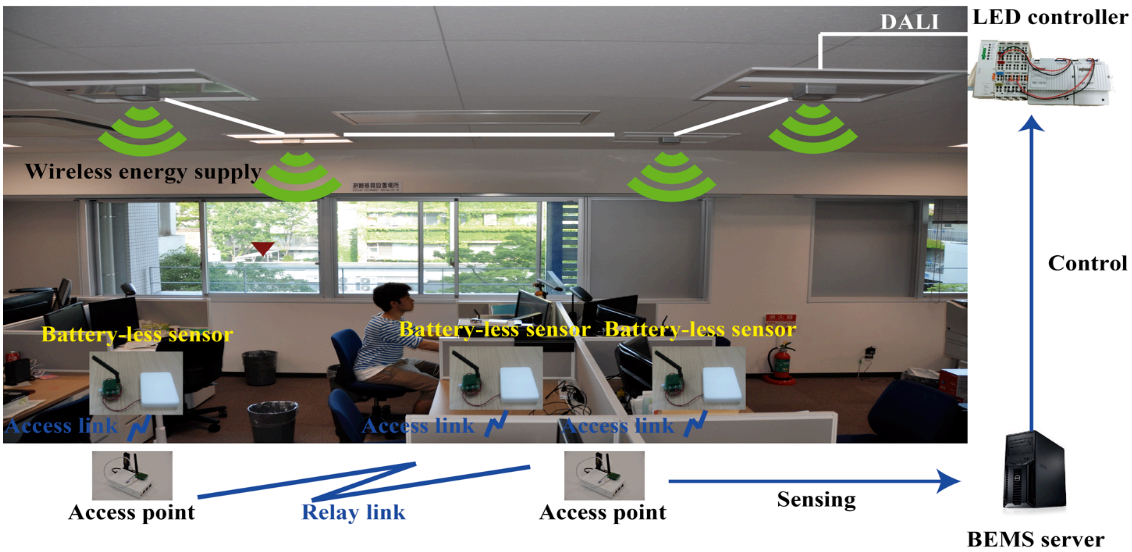


Fig. 1 Developed LED control system using battery-less sensor network.

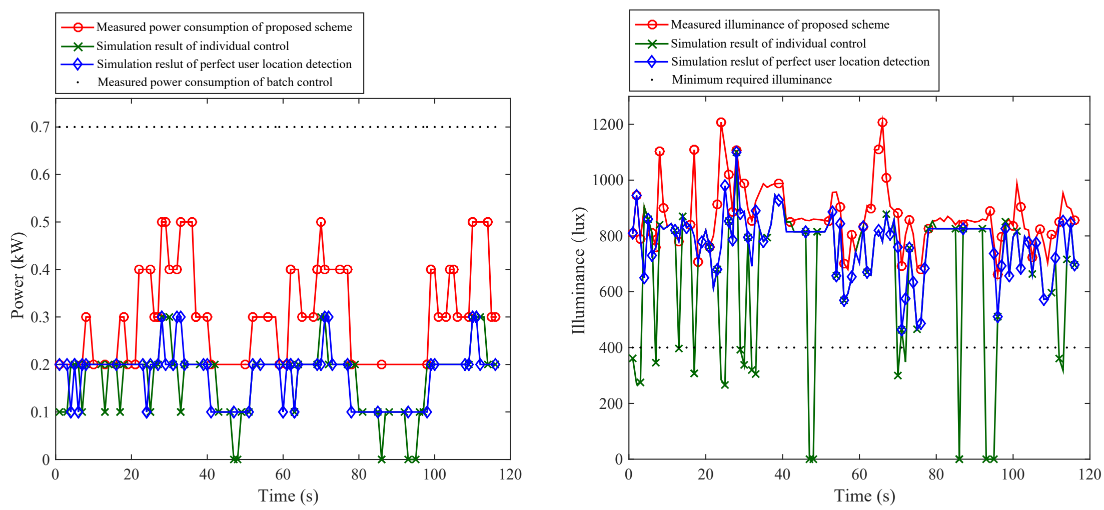
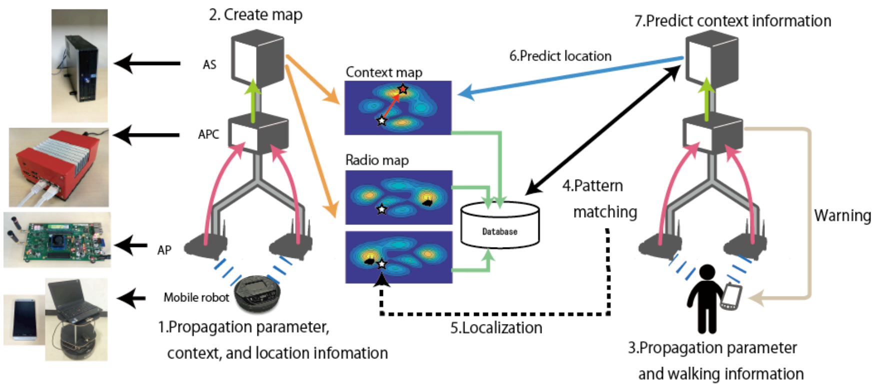


Fig. 2 Experimental results of lighting control.

Indoor Localization system for Healthcare Application[39]

We develop the context information prediction system using multi-sensor and indoor localization technologies based on fingerprinting technique as shown in Fig. 1, which is divided into learning, estimation, and prediction phases. At learning phase, the training terminal on the mobile robot sends signals, its location, and context information to APs. The APs convert the received signals into the propagation parameters (RSSI and RSPD) and then transfer them to AP controller (APC). APC receives and stores them in the database. Application server (AS) downloads them from the APC database and constructs radio and context map by the information. At estimation phase, a target terminal sends signals and walking information to APs. As with the same as the learning phase, AS receives the propagation parameters and walking information from the APs. Then, AS estimates the location of the target terminal by pattern matching with the parameters and radio map and walking information. At prediction phase, AS predicts the location of the target terminal ahead by N terms based on the estimated location and walking information; and then context information with context map and predicted location. If the predicted context information exceeds a threshold, AS warns target terminal.

We also evaluate the localization performance by an indoor experiment and the context information prediction performance on the simulator. The experimental parameters, environment and results are shown in Tab.1, Fig. 2 and 3 respectively. In the experiment, the mobile robot moves along the movement path in learning phase and the target terminal moves along the walking route in estimation phase. The results verify that RSPD+RSSI+walking information scheme achieves mean estimation error 1.36 m. In the simulator, AS predicts the context information using the location obtained from the above experiment and virtual context map. The results verify that false positive achieves 24% when probability of miss detection is 5% and N is 2 in Fig. 4.



Tab. 1 Experimental parameters.

Wi-Fi Standard	802.11a
Center Freq.	5.0 GHz
AP Num.	3
Antenna Num.	2

Fig. 1 Developed context information prediction system.

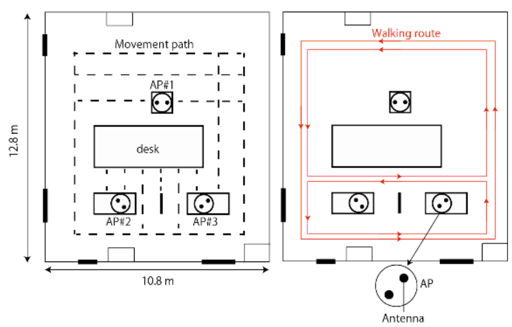


Fig. 2 Experimental environment.

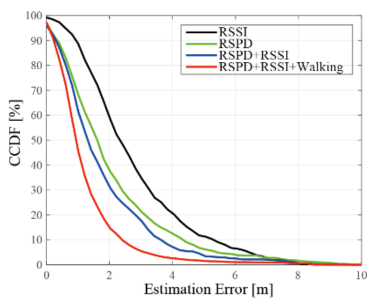


Fig. 3 Location Estimation Error.

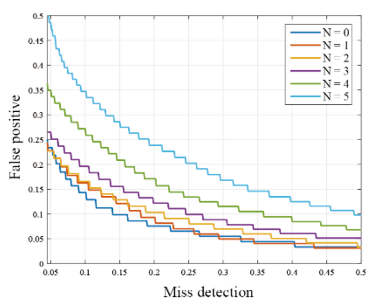


Fig. 4 Context prediction accuracy.

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

Professor Jun-ichi Takada

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

Assistant Professor Kentaro Saito

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

Assistant Professor Takuichi Hirano

Assistant Professor Takuichi Hirano received a B.S. in electrical and information engineering from Nagoya Institute of Technology, Nagoya, Japan in 1998. He received his M.S. and D.E. degrees from the Tokyo Institute of Technology, Tokyo, Japan, in 2000 and 2008, respectively. He is currently an Assistant Professor with the Tokyo Institute of Technology. He has been involved with electromagnetic theory, numerical analysis for EM problems and antenna engineering such as slotted waveguide arrays. He received the Young Engineer Award from IEICE Japan in 2004, IEEE AP-S Japan Chapter Young Engineer Award in 2004 and IEEE MTT-S Japan Chapter Young Engineer Award in 2011. He is a member of IEICE, IEEJ and IEEE.

Specially Appointed Associate Professor (Lecturer) Azril Haniz

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

Recent Research Topics

- **Channel sounding, propagation channel measurement and modeling**
  - Millimeter Wave Channel Sounding at 60 GHz for Future Heterogeneous Wireless Networks
  - Frequency Dependency Analysis of Radio Channels in Indoor Environment in SHF Bands
  - Measured Characteristics of Angular Power Spectra of Scattering at Different Exterior Materials in Indoor Environments at 60 GHz
  - Radio channel measurement in 12 GHz band by utilizing vector network analyzer and radio-on-fiber technology
  - Characteristic of Non-Specular Scattering on Outside Surface of Buildings at 25 GHz
  - Channel Modeling for VHF Band Broadband Communication System
  - Dynamic channel modeling through ray-tracing simulation for millimeter wave high speed vehicular communication system
- **Application of off-the-shelf software defined radio platform**
  - Development of channel sounder using commercial Software Defined Radio
  - Path loss measurement and modeling for wireless sensor network in precision agriculture application
  - Outdoor-to-Indoor Radio Propagation Measurement by using an Unmanned Aerial Vehicle in 2.4GHz band
- **Electro-magnetic analysis and antenna design**
  - Body-Attached Antenna for Breast Cancer Detection
  - Numerical Simulation of Body Area Communication with Consideration of Electromagnetic Wave Absorber Effects
  - Design of a Rectangular Patch Antenna for Radio Propagation Measurement
- **Radio localization**
  - Localization of Unknown Radios in Urban Environments

11 GHz band MIMO Channel Study [9][11][17][20][21][25][31][37][41][49][56]

(The project was funded by Ministry of Internet Affiars and Communications in FY2009-2012 as well as JSPS KAKENHI 15H04003/16K18102)

In the 5G system, the frequency bands from 6 GHz to 100 GHz, which are much higher than the frequency bands of the cellular network, are expected to be utilized for the mobile wireless communication. However, the radio propagation channel properties in these higher frequency bands have not been sufficiently justified from the view point of the requirements for current mobile data transmission. Therefore, we have conducted 11 GHz band channel measurements in indoor and outdoor environments in 2012 by utilizing a 24-by-24 Multiple-Input and Multiple-Output (MIMO) channel sounder. From the measurement, propagation delay and angular properties of the propagation channel were parameterized for quantitative discussion of the MIMO transmission performance.

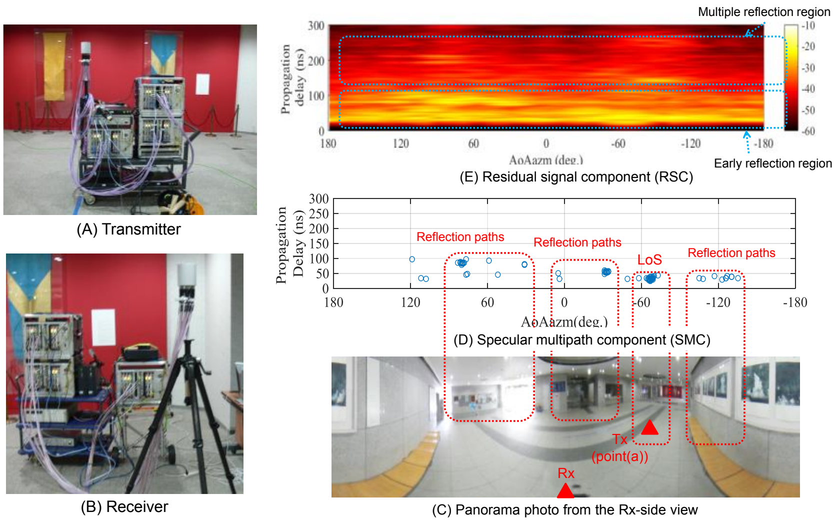


Fig. 11 GHz band MIMO Channel measurement

Millimeter Wave Channel Sounding at 60 GHz for Future Heterogeneous Wireless Networks [18][59]

(A collaborative research with Niigata University)

Due to congestion of the spectral resources in the sub 6 GHz frequencies, the millimeter wave bands in between 24.25 GHz to 86 GHz are being actively researched. The unlicensed 60 GHz millimeter wave band is considered for use in both the indoor (IEEE 802.11ad WLAN) and outdoor (5G) wireless networks. In this work, the measured wide-band double directional and polarimetric characteristics of the 60 GHz band in both the indoor and outdoor pico-cell environment, for access links, are studied. The clusters due to the line of sight, the first order reflection and diffraction are found to be the most significant (strongest) in outdoor environment (this is shown in the figure on the right). This indicates, ray tracing (RT) could be used to predict the significant clusters. The clusters due to scattering however are equally significant in indoor environment, RT therefore will not be able to predict the significant clusters. The angular spread does not show any polarization dependencies. The vertical polarization clusters are generally stronger than other clusters in both the environment. The results from in this work will be useful for designing millimeter wave systems, antennas and algorithms.

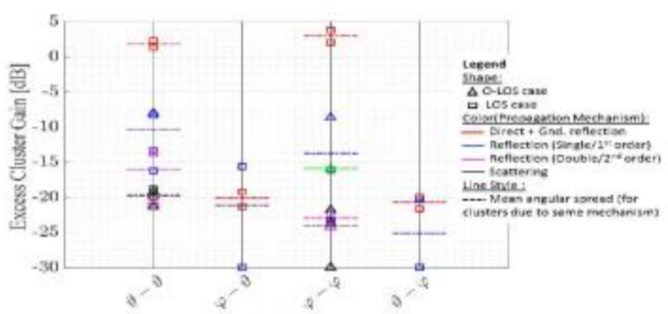


Fig. Excess cluster gain in outdoor environment

Frequency Dependency Analysis of Radio Channels in Indoor Environment in SHF Bands [55]

(A collaborative research with Antennas, Propagation and Radio Networking (APNET) Section, Department of Electronic Systems, Aalborg University)

Due to the increasing demand of higher data rate, the 5th generation wireless system utilizing higher frequencies has been considered. However, due to the high sensitivity of the high frequency signals, systems operating at lower frequency bands are still inevitable. Thus, it is very attractive to model and characterize the frequency characteristics over wide frequency ranges. In this study, we conducted the LOS channel measurement in several indoor environments using virtual uniform circular array (UCA) technique at three SHF bands: 3, 10 and 28 GHz. For preliminary analysis, we calculated the path loss (PL) and plotted against the free space PL (FSPL) in the indoor room environment as shown in Figure 1. It is found that due to significant diffuse scattering at 3 and 10 GHz bands, the measured PL is smaller than FSPL, whereas the measured PL for 28 GHz is around FSPL due to the dominance of LOS path.

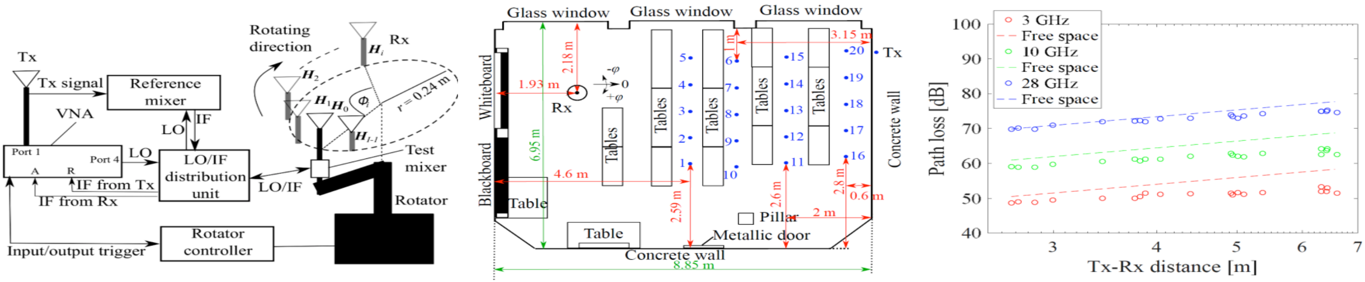


Fig.1 (Left) Measurement system. (Middle) Indoor room environment. (Right) PL characteristics compared with FSPL

Measured Characteristics of Angular Power Spectra of Scattering at Different Exterior Materials in Indoor Environments at 60 GHz [52]

(A collaborative research with New York University (NYU))

The properties of mm-wave bands are not fully studied yet, and especially diffuse scattering is considered to become the dominant physical mechanism. Therefore, we conducted a measurement campaign for understanding angular power characteristics of scattering.

The right-hand figure shows angular power characteristics that were plotted according to position/directions of receiver. #1~5 and the red-dashed line represent receiver positions and specular reflection directions, respectively. The measurement campaign was conducted at three exteriors, i.e. plastic/wood wall, glass/wood door and cloth wall, as well as at an aluminum plate for comparison. The result shows that all of the three have a much wider angular dispersion than reflection from aluminum plate. Especially, cloth screen has the biggest dispersion.

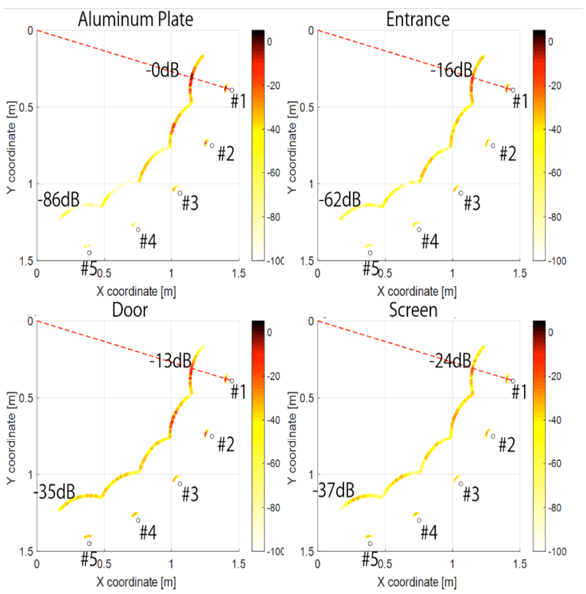


Fig. Birds-eye View Angular Power Spectrum

Radio Channel Measurement in 12 GHz Band by Utilizing Vector Network Analyzer and Radio-on-Fiber Technology

(Hardware developed by Koden Electronics Co. Ltd.)

Due to the rapid increasing of demand for the high throughput in mobile communication, the utilization of frequency bands above 6GHz has attracted huge research attention. In order to clarify its propagation characteristic, we developed the channel sounding system in the 12GHz band by utilizing vector network analyzer (VNA) and radio-on-fiber (RoF) technology. In our system, VNA is utilized to measure the transfer function of the channel. Advantage of the VNA for channel sounding is its capability to synchronize between transmitter and receiver with high precision. However, it has the disadvantage to require long coaxial cable for radio frequency (RF) for long distance measurements, which causes additional cabling loss. To solve this issue, we utilize the RoF technology for the RF signal transmission since it has low power loss compared with coaxial cable. As shown in Fig.1, the receiver antennas are connected to the VNA through the fast RF switch deployed in signal selection unit, and the channel transfer function for each Rx antenna can be measured in turn.

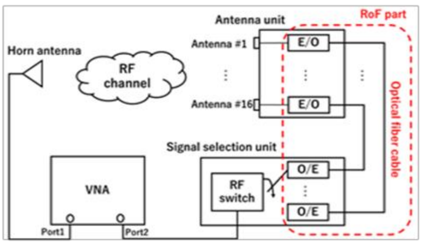


Fig.1 System diagram

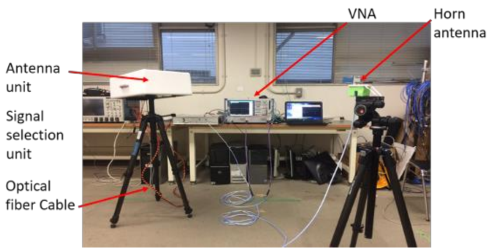


Fig.2 Measurement Setup

Characteristic of Non-Specular Scattering on Outside Surface of Buildings at 25 GHz [51]

(A collaborative research with NTT Network Innovation Laboratories)

Recently, wireless data traffic has increased rapidly. It is necessary to use wider bandwidth in order to increase the data rate at higher frequency bands. However, when frequency becomes higher, the first Fresnel zone will become very small that even human body could obstruct it. This research focuses on the non-specular scattering and aims to make a model to predict the non-specular scattering. In order to achieve that, the measurement had been done by pointing two directional antennas on the same point on the building surface, in order to measure the scattering coefficient of the wall. Comparing between measured results and simulated results assuming specular reflection only, the spread of the measured peak in x direction is observed.　This means that non-specular scattering effect is observed.

Fig.1. Measurement at tile and metal

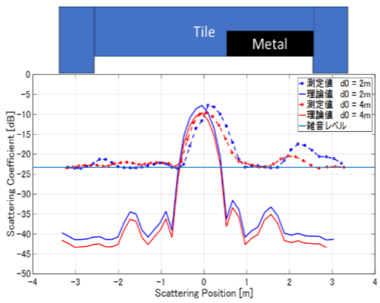


Fig.2. Result of tile and metal

Dynamic Channel Modeling Through Ray-Tracing Simulation for Millimeter Wave High Speed Vehicular Communication System [48]

In order to improve the data transmission rate, the use of higher frequency that allows to transmit with larger bandwidth is a key technique. However, one of the most challenging problems of using high frequencies is that when the mobile station (MS) moves with high speed, the variation of channel impulse responses (CIR) may become severe. Thus, the variation of CIR in small scale needs to be evaluated. For this purpose, in this study a dynamic channel model at 45 GHz frequency band for high-speed vehicular communication systems through the ray-tracing simulation was developed. In this study, firstly the ray-launching based ray-tracing simulation was performed to obtain the propagation data. The obtained data includes parameters of propagation paths as coordinates of interaction points, path delay, path power, phase, angle of departure and arrival. Because this data was obtained only at discrete positions of MS, the linear interpolation approach was performed to obtain the data for the continuous positions. In this approach, the parameters of propagation paths at any position of the MS such as delay and received power can be estimated by using the parameters of two nearest positions of MS which were already obtained from ray-tracing simulation. The figure shows the ray-tracing simulation scenario and the power delay profile of dynamic channel. The original interval in simulation of MS was 1 m and it can be reduced to 1 mm by interpolation.

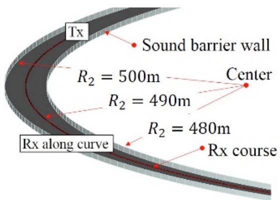


Fig.1. Simulation

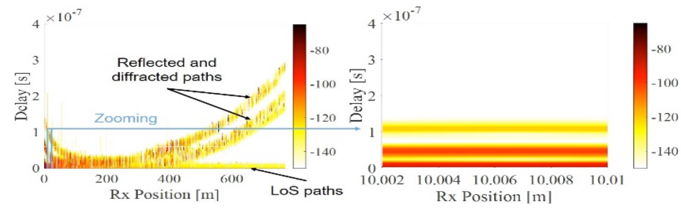


Fig.2. Dynamic channel power

Channel Modeling for VHF Band Broadband Communication System [19] [54]

(A collaborative research with National Institute of Information and Communications Technology (NICT))

After digitization of analog TV broadcasting in Japan, a part of the VHF band (170-202.5 MHz) was allocated for public broadband mobile communication (PBB) system as shown in Fig. 1. The purpose of this study is to characterize the broadband radio channel in this band to evaluate the applicability of the system in various environments. In order to develop a channel model, impulse response measurement has been conducted by using a transmitting signal based on ARIB STD-T103. At receiver side, a signal analyzer was used to capture receiving signal as complex IQ data. The impulse responses were obtained by calculating sliding correlation between reference signal and measured signal. Figure 2 shows an example of impulse response measured in non-line-of-sight urban environment. By using analyzed responses, a statistical channel model is developed.

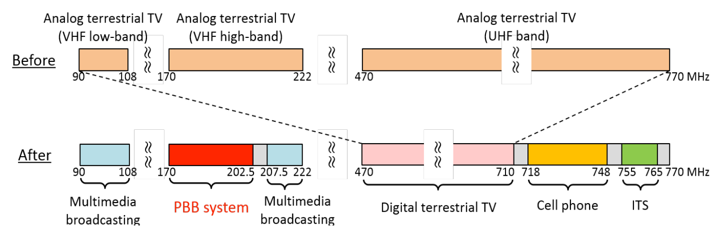


Fig. 1. Spectrum allocation plan in Japan

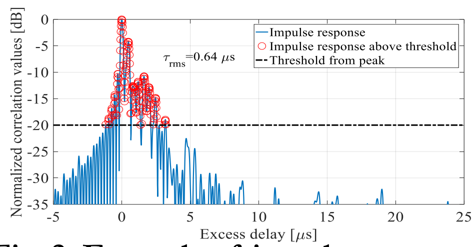


Fig. 2. Example of impulse response

Development of channel sounder using commercial Software Defined Radio

Channel measurement is necessary to accurately clarify propagation channel characteristics. Low cost and flexible channel sounder is preferred for measurement purpose. Accuracy of directional channel characteristics depends on the accuracy of carrier phase synchronization between transmitter and receiver. This work aims to develop the low cost channel sounder for directional channel measurement using Universal Software Radio Peripheral (USRP) and GNU Radio software. GNU Radio installed in host PC and USRP together form the general purpose radio. USRP is purchased from Ettus Research which has the flexibility of using RF frequency over 1200 to 6000 MHz frequency band. GPS Disciplined Oscillator (GPSDO) is considered to be used for the carrier phase synchronization purpose. GPSDO consists of the free running oscillator (TXCO) which can also synthesize 10MHz frequency from 1 PPS reference signal received by GPS receiver. Use of GPSDO gives the flexibility for outdoor measurement scenario. GPSDO can also be used in indoor measurement by installing GPS antenna in the rooftop and extending it to indoor measurement location through low loss RF cable, LMR-400.

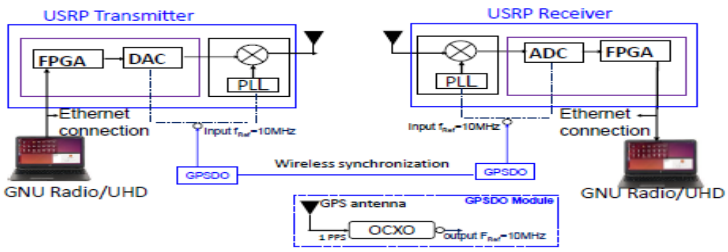


Fig. Architecture of USRP and GNU Radio based channel sounder

Path Loss Measurement and Modeling for Wireless Sensor Network in Precision Agriculture Application [47]

(A collaborative research with National Electronics and Computer Technology (NECTEC), Thailand and funded by the Fujikura Foundation.)

Precision agriculture is the management of spatial and temporal variability of the fields in order to maximize the yield. Wireless sensor network (WSN) plays the important role in gathering such variability for the precision management. To ensure the WSN coverage, the propagation path loss model in agriculture environment is necessary. The measurements had been conducted in the agriculture fields in Thailand by using the channel sounder developed. The relative angle between the line of plantation and the direction from Tx to Rx is found as one of significant factors which causes the radio propagation loss. In case of sugarcane filed, such angular loss (P_{ori}) which is normalized by the distance-dependence path loss is shown in Figure.

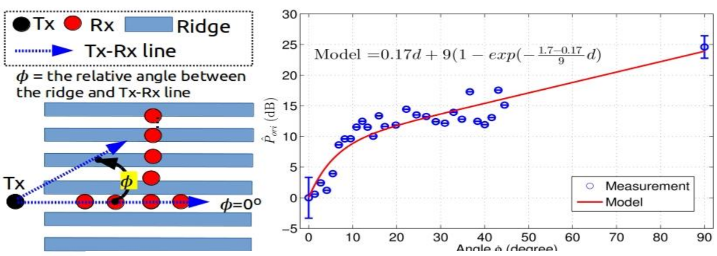
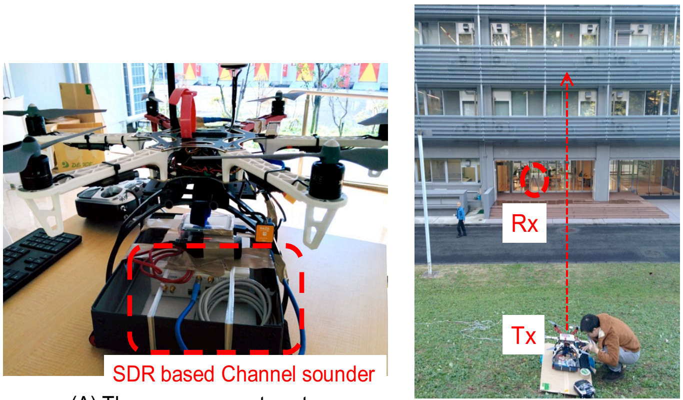


Fig. Angular dependency of path loss

Radio Propagation Loss Measurement using Unmanned Aerial Vehicle [53]

(The project was funded by the Fujikura Foundation.)

In urban areas, it is necessary to accommodate users in high-rise building efficiently for the service area planning in mobile wireless networks. In this work, we conducted the radio propagation loss measurement in 2.4 GHz band and 4.8 GHz band for the outdoor to indoor high-rise building scenario by using an unmanned aerial vehicle (UAV). In the 2.4 GHz band measurement, the mobile WiMAX router was mounted on the UAV, and the RSSI was measured at a variety of UAV positions. In the 4.8 GHz band measurement, the compact channel sounder developed on the commercial software-defined radio platform was mounted on the UAV. We are planning detailed radio propagation measurements for contributing to the more efficient service area planning of wireless networks.



(A) The measurement system (4.8 GHz band)

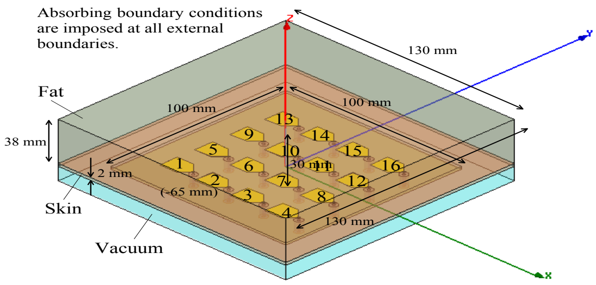
(B) The measurement overview

Radio Propagation Loss measurement using UAV

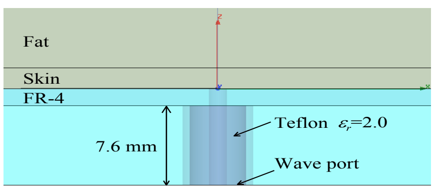
Body-Attached Antenna for Breast Cancer Detection [22]

(A collaborative research with Hiroshima University)

Early detection of breast cancer is a matter of important issue. UWB band (3 GHz-10 GHz) band is considered for radar detection of breast cancer by utilizing difference of dielectric constant. A 4 x 4 pentagonal patch array antenna using an FR-4 substrate (Fig. 1) is proposed for the antenna element. Antennas were designed by considering the effect of human body. The measured and calculated frequency characteristics of S-parameters (Fig. 2) matched well. The amplitude of reflection coefficient was less than -5 dB for frequency range larger than 2.2 GHz. Linear frequency characteristics of phase in S-parameters is obtained, which is very important property for non-distortion characteristic of waveform.

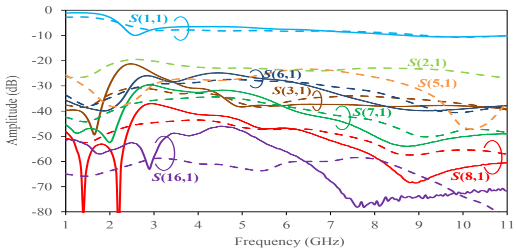


(a) Perspective view

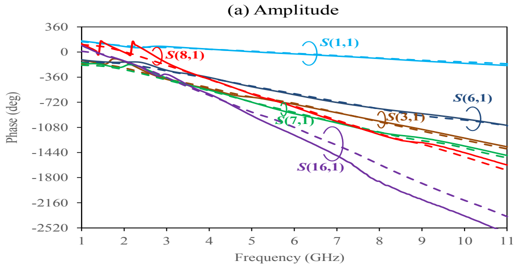


(b) Cross-sectional view

Fig. 1. A 4 x 4 pentagonal patch array antenna.



(a) Amplitude



(b) Phase

Fig.2. Frequency characteristics of S-parameters.

Numerical Simulation of Body Area Communication with Consideration of Electromagnetic Wave Absorber Effects [15]

(A collaborative work with Aoyagi Lab.)

To reduce interference from surrounding environment and make a simple on-body propagation channel, body area measurement is often conducted in an anechoic chamber. However, unexpected measurement results still happen which could not be identified. It is suspected that the characteristics of wave absorbers installed on the internal surfaces of chamber might have some influence to on-body propagation channels. In this study, the simulation approach based on the frequency-dependent FDTD method is developed to investigate the effects of the on-floor wave absorbers (closer to human subject) to the on-body channel characteristics. Two different absorber structures, the multi-layer planar and array pyramid (placed below the posture), are used and compared with the calculation model without absorber. The simulation results (see Fig. 1) show that when source is moved relatively closer to the on-floor absorbers, the received E-field signals are affected with discrepancy (greater than 10 dB) at some frequencies, receiver locations, and certain orientation of transmitter and receiver.

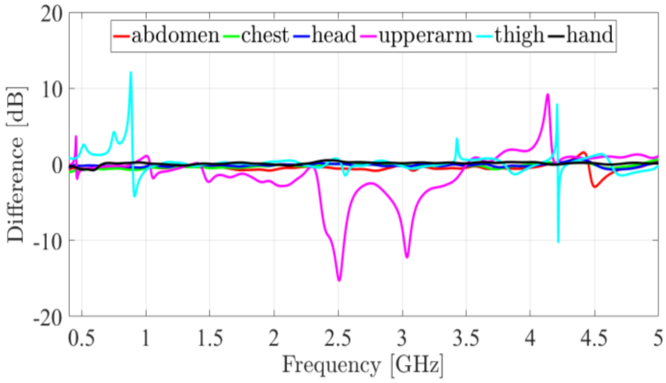


Fig. Frequency response comparison between the model with pyramid absorber and without absorber for Tx on the ankle and Tx-Rx in z direction.

Design of a Rectangular Patch Antenna for Radio Propagation Measurement [57]

In the next generation 5G systems, higher frequency band will be used and our group is focusing on measurement of the channel characteristics at 5GHz frequency band by using USRP channel sounder systems. Lightweight antenna is desired in a channel sounding equipment. Therefore, a patch antenna with 5GHz center frequency will be designed for both transmitter and receiver of USRP channel sounder. A rectangle patch antenna was designed for channel sounder at 5GHz band. An antenna was fabricated and measured. Frequency shift was observed from simulation. The frequency shift may due to the estimation error of dielectric constant of the substrate.

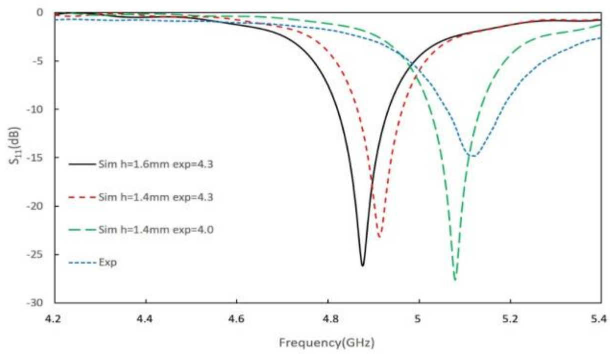


Fig. Comparison between different thickness and dielectric constant and experiment data

Localization of Unknown Radios in Urban Environments [10][29][42][58]

(A collaborative work with Koden Electronics Co. Ltd. and Sakaguchi Lab.)

Unknown radios have the potential to cause harmful interference to existing radio systems, thus it is crucial to localize these radios in order to stop their transmission and prevent service disruption. In this research, a novel algorithm to localize unknown radios in urban environments is proposed. The fingerprinting technique is employed, which is expected to perform better than conventional localization techniques such as triangulation in urban environments where there may be many obstacles obstructing the direct line-of-sight path between the unknown radio and the receiver sensor.

In our proposed technique, the cross-correlation of the channel impulse response is used as fingerprints, and these fingerprints are interpolated in the multiple domains in order to support localization of unknown radios which may be transmitting at any arbitrary signal bandwidth and center frequency. For dynamic tracking of moving unknown radios, we have employed the particle filter. Our proposed implementation can significantly reduce computational time by adaptively selecting a subset of training fingerprints for interpolation, and this could be achieved with minimal sacrifice in localization accuracy. Localization performance of the proposed algorithms is evaluated through electromagnetic propagation simulations using commercial software.

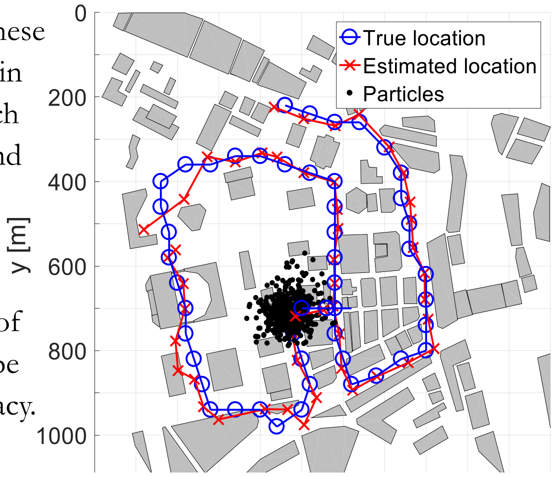


Fig. Tracking accuracy of proposed algorithm

Development of Low Cost Indoor Localization System by using Raspberry Pi [46]

Due to the increasing demand for the localization Based Service (LBS), wireless localization technologies have become very popular. Because GPS does not work well in indoor environments, indoor localization has become a focus of research and development recently. In this research, a low-cost device-free indoor localization system by using Raspberry Pi is proposed. The fingerprinting technique is employed. In our proposed system, the Received Signal Strength (RSS) of Bluetooth Low Energy (BLE) is used as fingerprints. Raspberry Pi is utilized as BLE beacons to implement the indoor localization system. Raspberry Pi is a low-cost small single-board computer. It can transmit and receive BLE signals by mounting BLE USB dongle. Using this property, we can make algorithm of Indoor Localization more flexible. We also use VNC to control the Raspberry Pi remotely and use UDP to transfer data between devices and server.

Fig. Photo of Raspberry Pi

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Professor Kazuhiko Fukawa

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

Assistant Professor Yuyuan Chang

was born in 1975. He received the B.E. degree from Department of Control Engineering and the M.E. degree from Department of Electrical Control Engineering, National Chiao Tung University, Hsinchu, R.O.C. (Taiwan), in 1997 and 1999, respectively, and another M.E. and the D.E. degree from Electrical and Electronic Engineering Department, Tokyo Institute of Technology, Tokyo, Japan, in 2007 and 2011, respectively. He served in Industrial Technology Research Institute, Hsinchu, R.O.C. (Taiwan), from 2000 to 2005. He has been with Tokyo Institute of Technology from 2011 as a research fellow. Since April of 2016, he has been an Assistant Professor of Tokyo Institute of Technology. His research interests include multi-user MIMO systems, user scheduling algorithm, MIMO sounder and millimeter wave wireless systems. He is a member of IEICE and received the Best Paper Award of IEICE Communications Society in 2013

Our Research Interests

At Fukawa laboratory, we have been conducting both fundamental and applied researches involving signal processing techniques for mobile communications. Recently, we have focused on transmission systems, especially MIMO-OFDM, multiple access, modulation and demodulation schemes for cognitive radio, 10 Gbps super high-bit rate mobile communications, and millimeter wave. Below is a detailed list of our research topics in recent five years.

Research Topics in Recent Five Years

Transmission System

MIMO detection & CSI estimation

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

MIMO-OFDM system optimization

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

Super high rate mobile communications

- 8×16 MIMO multi-Gbps systems

Multiple Access

Collision detection

Interference mitigation

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

Access scheme

- IDMA with iterative detection
- Random packet collision solution

Wireless Security

Random phases based physical layer security

Millimeter Wave 10 Gbps

Phase noise compensation

I/Q imbalance compensation

Real zero coherent detection

In-House Simulator Design & Implementation

FPGA on-board system simulators

4x4 MIMO fading simulators

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

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Interference Cancellation Employing Replica Selection Algorithm and Neural Network Power Control for MIMO Small Cell Networks [1][3]

In this research, a network with dense deployment of multiple-input multiple-output (MIMO) small cells is considered. The overlap of coverage among small cell base stations (BSs) produces inter-cell interference, which degrades system capacity. This research aims to provide an inter-cell interference management (IIM) scheme that maximizes the system capacity by using both power control for inter-cell interference coordination (ICIC) on the transmitter side and interference cancellation (IC) on the receiver side.

The power control determines downlink (DL) transmit power levels at the BSs by employing a neural network (NN) algorithm over the backhaul, as shown in **Fig. 1**. The assumption is made that time-division duplex (TDD) is employed. The NN weights are estimated during an offline training period before the actual transmission so that the NN output can readily represent the probability of BS transmit power level. The training is conducted by a supervised gradient based method known as the backpropagation algorithm.

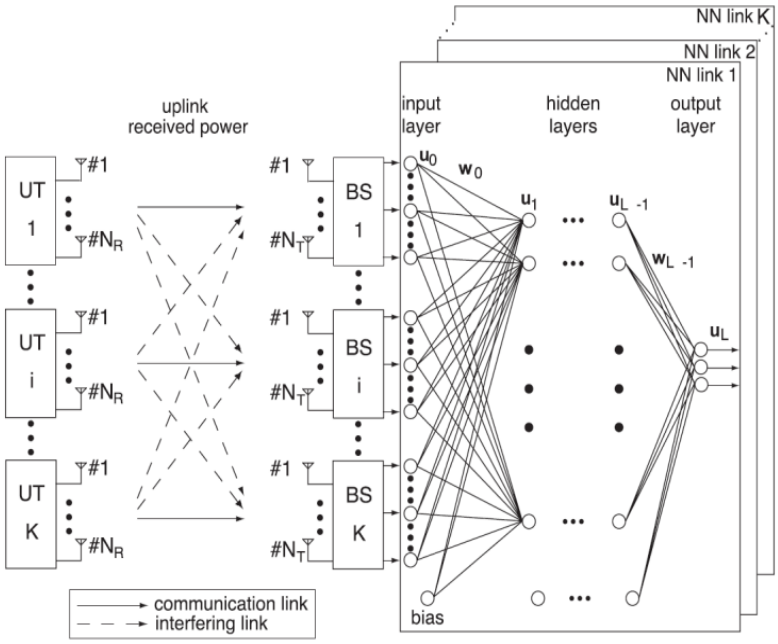

Fig. 1. A neural network system for DL transmit power control

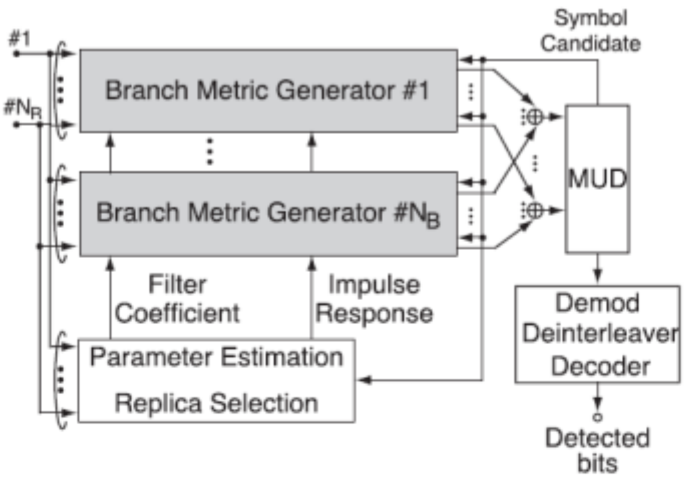

Fig. 2. A structure of a receiver with joint processing of WMFs and MUD

To further improve the signal to interference plus noise ratio (SINR), every user equipment (UE) employs a multiuser detector (MUD) as IC. **Fig. 2** shows the structure of the receiver. The MUD detects not only the desired signals, but also some interfering signals to be cancelled from received signals. The receiver structure consists of branch metric generators (BMGs) and MUD. BMGs suppress residual interference and noise in the received signals by whitening matched filters (WMFs), and then generate metrices by using the WMFs' outputs and symbol candidates that the MUD provides. On the basis of the

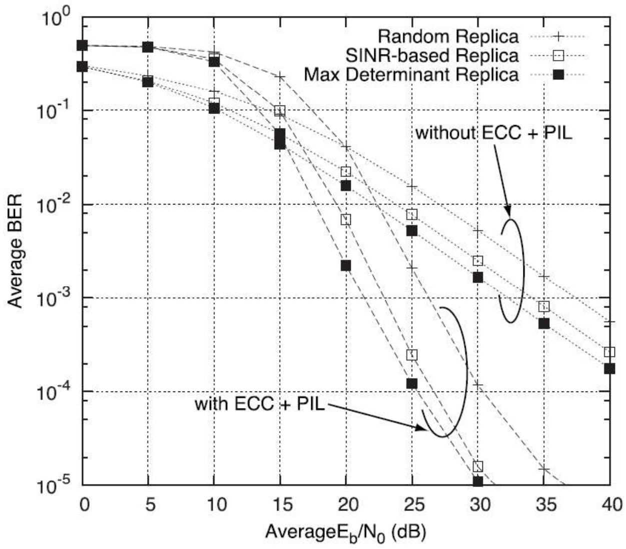

Fig. 3. BER performance with three selection algorithms

metrices, the MUD detects both the selected interfering signals and the desired signals. In addition, the MUD determines which interfering signals are detected by an SINR based replica selection algorithm.

Computer simulations demonstrate that the SINR based replica selection algorithm, which is combined with channel encoders and packet interleavers (ECC and PIL), can significantly improve the system bit error rate (BER), and that combining IC at the receiver with NN power control at the transmitter can considerably increase the system capacity and can obtain system capacity with comparable loss, and less computational complexity compared to the conventional greedy algorithm.

Fig. 3 shows the BER performance of IC with several algorithms to select interfering signals for the detection and cancellation, when the number of transmit antenna $N_T = 2$, the number of receive antenna $N_R = 3$, and received signal power from every BS is the same.

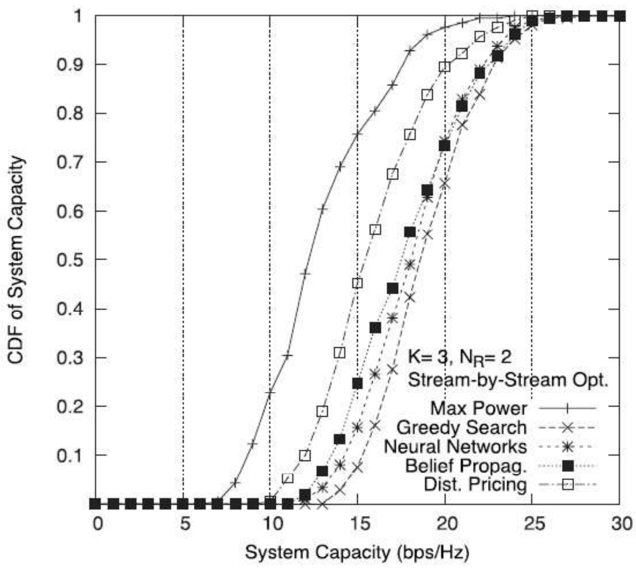

Fig. 4. CDF of the system capacity for the stream-by-stream optimization with power control algorithms (NR = 2)

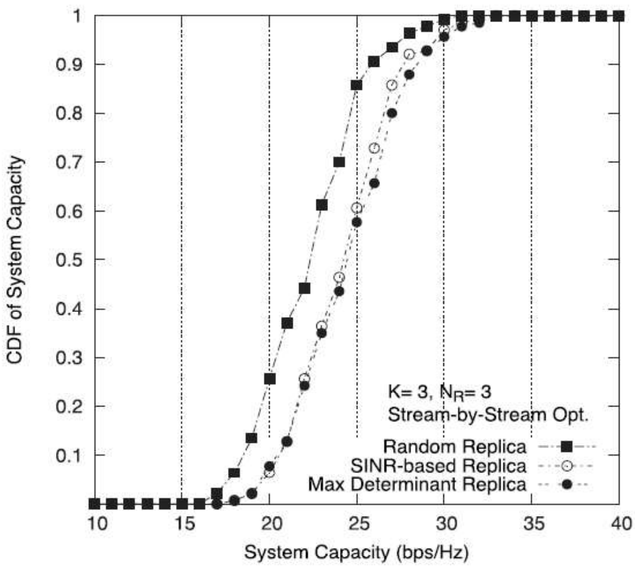

Fig. 5. CDF of the system capacity by the NN power control with stream-by-stream optimization

Fig. 4 shows the performance of the stream-by-stream optimization with various power control algorithms when the number of link $K = 3$ and $N_R = 2$. It can be seen that the NN algorithm can achieve almost the same performance as the greedy search algorithm while requiring much less complexity. **Fig.5** shows the CDF of the system capacity by the NN power control algorithm with the stream-by-stream optimization when $K = 3$ and $N_R = 3$.

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A Linear Combining Scheme to Suppress Interference in Multiple Relay Systems [2]

This research aims to propose an interference suppression scheme based on linear combining for multiple relay systems. In this research, a downlink (DL) half-duplex multiple relay system is considered. Interference from base stations and relays in neighboring cells degrades the bit error rate (BER) performance of mobile stations (MSs) near cell boundaries.

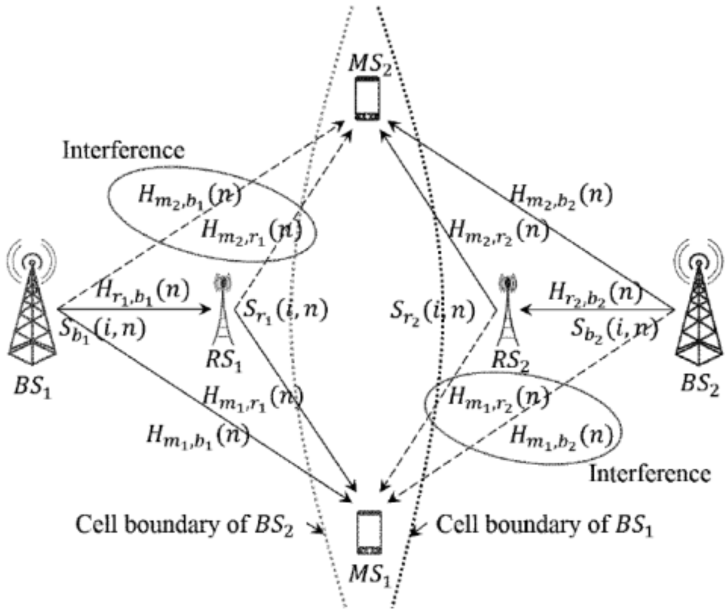

Fig. 6. A DL half-duplex multiple relay system

Fig. 6 shows the system model considered in this research. There two base stations (BSs), with corresponding relay stations (RSs) and MSs. There exist two transmission phases. In the first phase, BSs are synchronized and transmit signals for the corresponding MSs. In the second phase, the RSs are synchronized and transmit signals for the corresponding MSs. The transmitted signals and received signals of a *Np*-symbol long packet with *Nd*-symbol long delay are shown in **Fig. 7**, where the subscript *bn* denotes the signal from the *n*-th BS, *rn* denotes the signal from the *n*-th RS, and *ml* denotes the *l*-th MS. Each MS receives interfering signals in addition to the desired signals during the two phases.

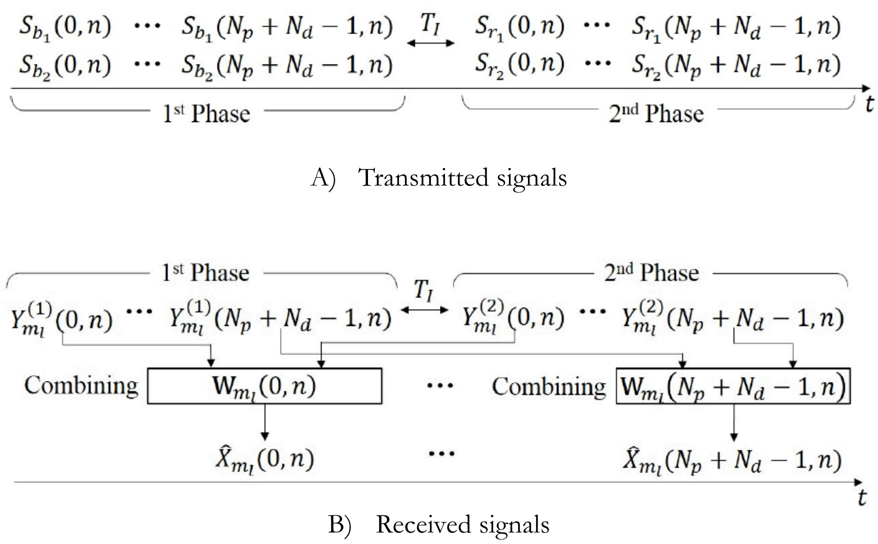

Fig. 7. Signals in the first and second phases

To suppress such interference, the proposed scheme linearly combines received signals of the first and second phases at MS. Different from those conventional schemes that requires channel state information (CSI) feedback in order to acquire the weight coefficients, the proposed scheme requires only information on preamble symbols of the target MS.

Without CSI feedback, weight coefficients for the linear combining are estimated by the recursive least-squares (RLS) algorithm.

Fig. 8 shows the block diagram of the RLS-based combiner. The superscript (1) and (2) indicate the signals received at the first and second phases respectively. The detected bits are used to regenerate the signals replica, which makes the RLS algorithm estimate the weight coefficients more accurately.

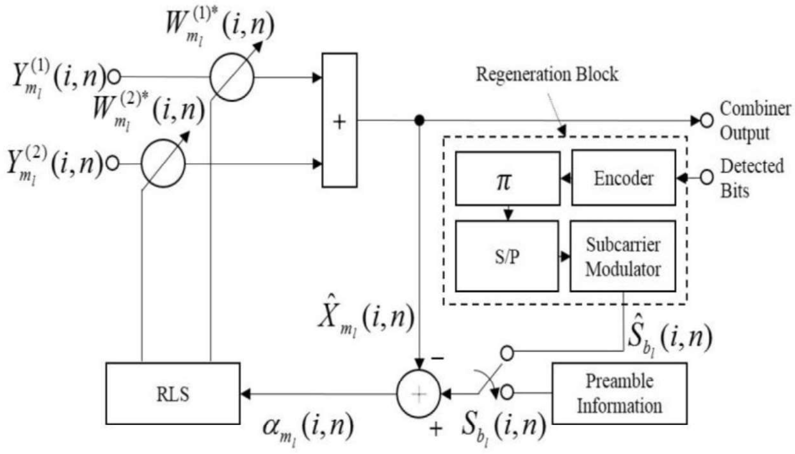

Fig. 8. A block diagram of the RLS-based combiner

Computer simulations of orthogonal frequency-division multiplexing (OFDM) transmission under two-cell and frequency selective fading conditions are conducted. Both the decode-and-forward (DF) and the amplify-and-forward (AF) RS are evaluated.

Figs. 9 and **10** compare the average BER performance of the RLS-based combining, RLS-based

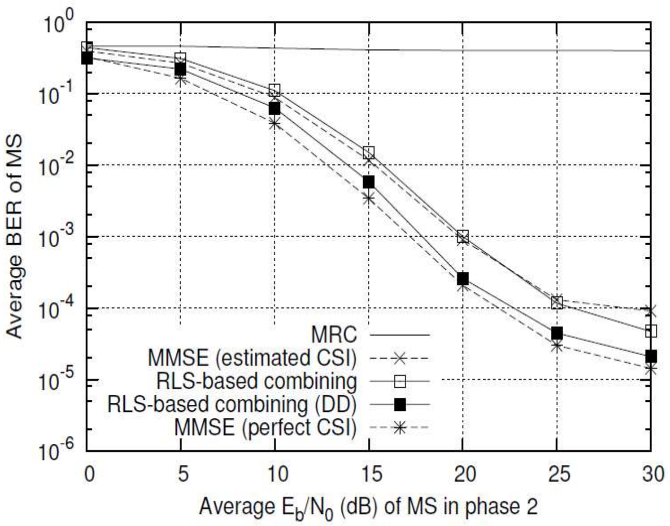

Fig. 9. BER performance of AF, with E_b/N_0 of RS being 20 dB, and PL=4

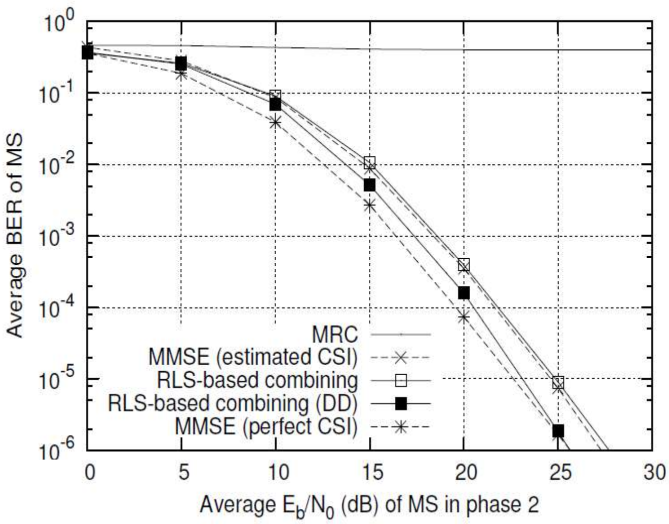

Fig. 10. BER performance of AF, with E_b/N_0 of RS being 20 dB, and PL=4

combining with decision directed (DD), MMSE combining with perfect and estimated CSI, and maximal ratio combining (MRC), when the length of the preamble symbol PL = 4 and RS employs AF and DF, respectively. The average power of signals received at the MS during the first phase is 10 dB weaker than that during the second phase. The proposed RLS-based linear combining with decision directed (DD) estimation is superior to the RLS-based linear combining using only the preamble and can outperform the minimum mean-squared error (MMSE) combining with estimated CSI.

Separation & Detection of Collided Packets in the Space-based AIS [5][6][13]

This research aims to propose a scheme in order to separate and detect the collided packets in the space-based Automatic Identification System (AIS). Information of AIS can be obtained across the open sea by satellites. In Japan, JAXA has conducted a SPace-based AIS Experiment (SPAISE). In this research, satellites equipped with AIS receivers have been launched to altitude 600 km and receive AIS signals suffering from Doppler shift. The results of the research clarify that the wide coverage of the satellite causes collision of many AIS signal packets, which makes signal detection very hard. **Fig. 11** illustrates the situation of a satellite coverage area. Since the satellite coverage area at a certain time is much larger than the land station coverage area, there happens some collision of AIS signal packets in the AIS receiver. Therefore, in order to separate and detect the collided AIS signal packets, we propose a separate and detection method exploiting correlation detection and SIC.

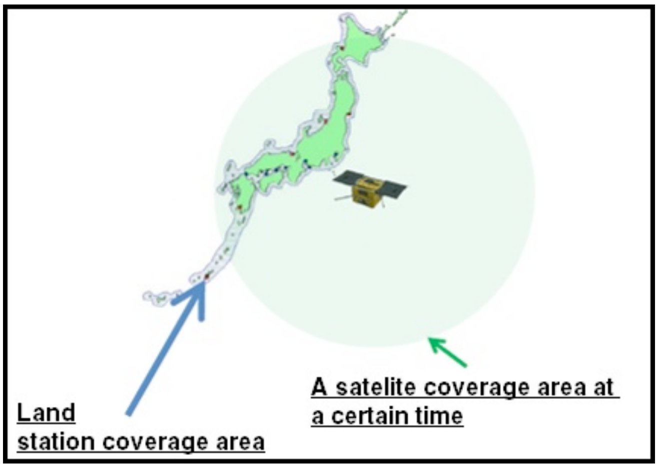

Fig. 11. A satellite/land station coverage area

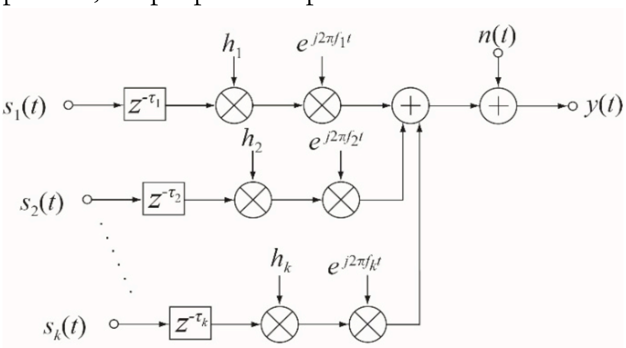

Fig. 12. A signal model of AIS signals

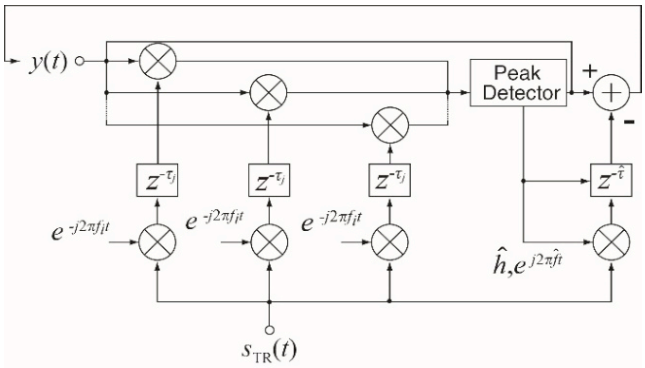

Fig. 13. A diagram of Correlation Detector

Fig. 12 illustrates the signal model of AIS signals. The received signal $y(t)$ consists of the GMSK-modulated transmit signals, which are affected with Doppler shift, delayed time, and complex envelope. These signals and receiving noise are added in the receiver.

First of all, we propose a parameter estimation method of AIS signals exploiting correlation detection between received signals and the training sequence.

Fig. 13 illustrates the diagram of the correlation detector. In this system, the phase of the training sequence is rotated by the candidates of the Doppler frequency and then its received timing is delayed by candidates of delayed time. Then the correlation between the resultant training sequences and the received signals is calculated. By searching for the highest peak of the correlation, we can determine the Doppler frequency and delayed time of the dominant AIS packet. The training sequence with the estimated Doppler frequency and delayed time is subtracted from the received signals. The correlation between resultant received signals and training sequences is recalculated. These processes are repeated

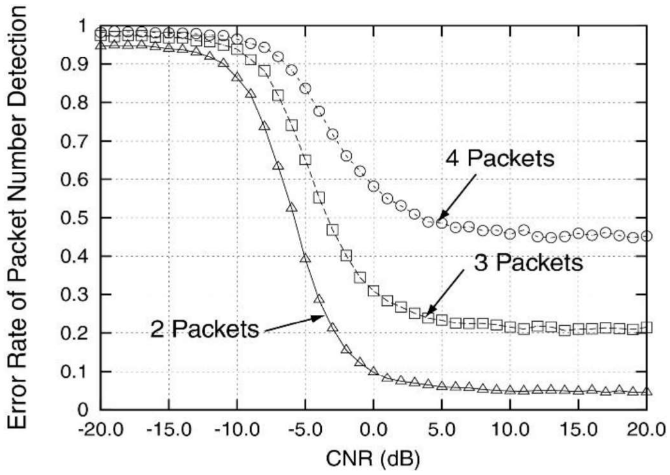

Fig. 14. Error Rate of Packet Number Detection

until the peak of the correlation does not exceed a threshold, which we can estimate the parameters of collided packets.

Fig. 14 shows the result of the computer simulation about the error detection rate of the number of collided packets. We assume in this simulation that the average received powers are the same among all collided packets. In this figure, we can see that when the average CNR is low, the error rate becomes very high. This should be because the accuracy of training signal generation becomes low with the error of the estimated parameters deteriorating. We can also see that the error rate becomes approximately 45% when the number of collided packets is 4, 20 % for 3, and 5% for 2.

In addition to the estimation of the number of collided packets, we adopt Successive Interference Cancellation (SIC) for separate detection. **Fig. 15** illustrates the diagram of SIC. As mentioned above, the Doppler frequency, delayed time and complex envelope of each collided packet are estimated using the correlation detector. By inputting the estimated parameters and the received signal, we can execute the SIC. SIC first detects AIS signals in the order of the average received power using differential detection. Then, the replica signals consisted of the detected signals and the estimated parameters are subtracted from the received signal. The resultant received signals are inputted again in the differential detector. These processes are repeated until no AIS signals are detected in the received signal.

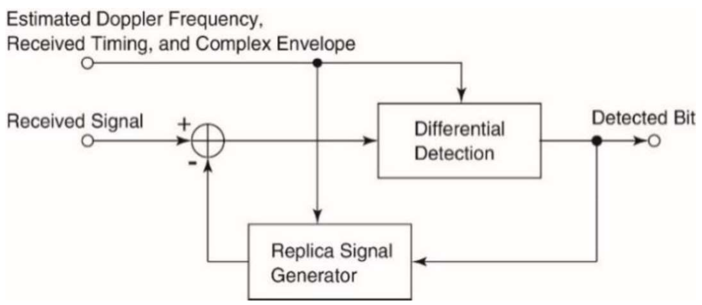

Fig. 15. A diagram of Successive Interference Cancellation

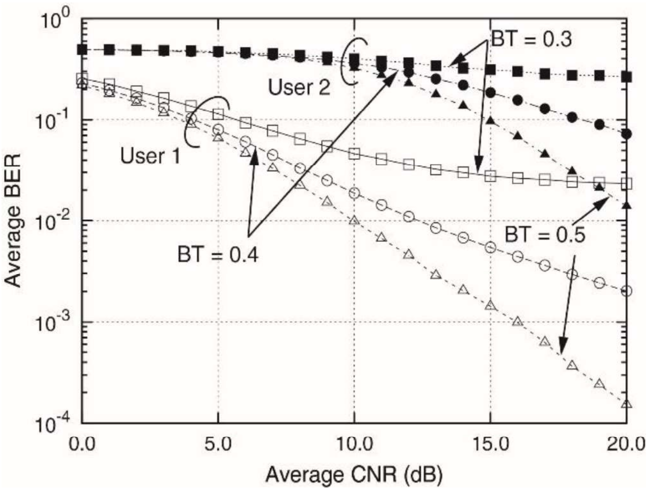

Fig. 16. Average Bit Error Rate

Fig. 16 shows the result of the computer simulations about the average Bit Error Rate (BER) of collided packets. The estimation of the number of the collided packets in this simulation is assumed to be ideal, and the number of collided packets is fixed to 2. Similarly, the difference of average received powers is supposed to be 10 dB. In this figure, we can see that the average BER of 10^{-3} can be achieved for User 1 (outline figures, relative largest received power) when the average CNR is about 16.0 dB and BT is 0.5. Moreover, we can find that the average BER of 10^{-2} can be achieved for User 1 when the average CNR is about 12.5 dB and BT is 0.4.

Semi-blind Interference Cancellation for Heterogeneous Networks using Single Receive Antenna [8][11]

As shown in **Fig. 17**, this research considers a heterogeneous network (HetNet), which consist one desired base station (BS) and multiple interfering BSs of different types.

In order to cope with severe inter-cell interference (ICI) on the user equipment (UE) with limited space, this research focuses upon the nonlinear interference cancellation scheme on the UE side, and tackles the most challenging problem of interference cancellation with single receive antenna.

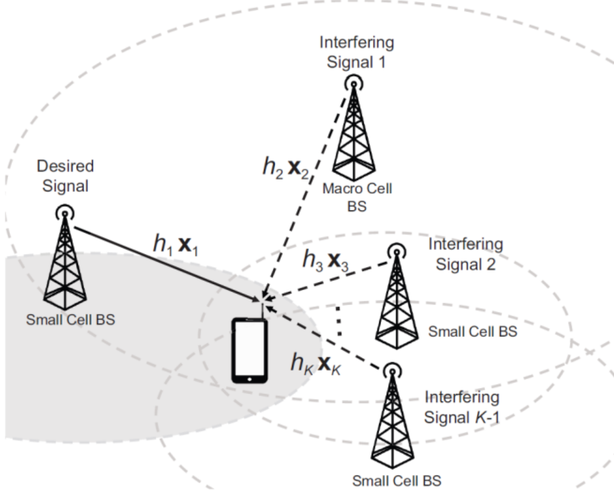

Fig. 17. A heterogeneous network

The proposed scheme is based on a *quantized channel approach* and does not require multiple receive antennas or knowledge about training sequences of the interfering signals. The interference detection and cancellation requires accurate channel state information (CSI), which can be achieved by either announcing interfering signals' training sequences or using the blind channel estimation techniques. However, major mobile communication systems do not inform users on other users' preambles. Given a sequence of received signals during the training period, the joint channel estimation and signal detection (JCESD) can blindly estimate CSI of the interfering signals. The maximum likelihood detection (MLD), which can be considered the optimum JCESD, must perform channel estimation for all transmitted signal candidates of the interfering signals and must search for the most likely signal candidate. Therefore, MLD requires a prohibitive amount of computational complexity.

To reduce such complexity drastically, several suboptimal JCESD have been proposed. The Viterbi algorithm (VA) based schemes combines the VA and the recursive least squares (RLS) algorithm or the least mean square (LMS) algorithm, which updates a channel estimate for each path in the trellis and maintains multiple survivors under the maximum likelihood (ML) criterion at each stage. However, eliminating some signal candidates before the convergence can lead to degradation.

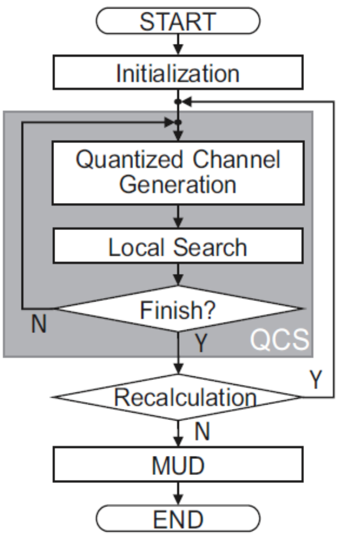

Fig. 18. Flow chart of the proposed scheme

The proposed scheme enhances the *quantized channel approach*, and applies the enhanced version to JCESD. It iteratively searches for generated channel estimates and the corresponding detected signals under the ML criterion, and does not have the problem that VA has as mentioned above.

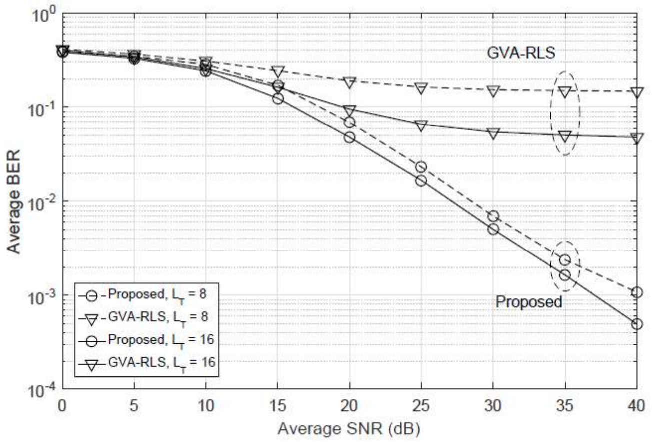

Fig. 19. Average BER performance compared with GVA based scheme (3 dB, −3 dB)

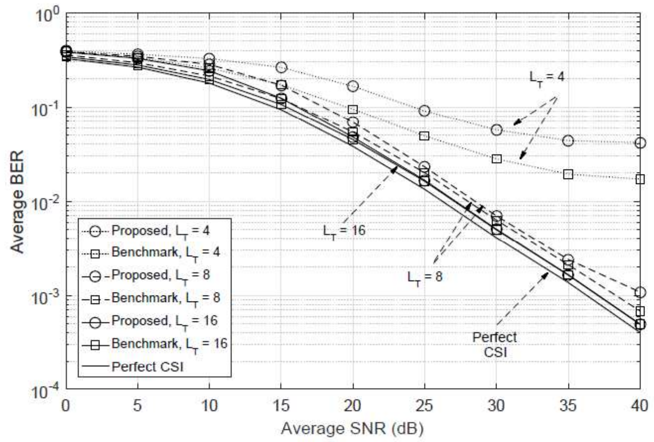

Fig. 20. Average BER performance compared with Benchmark (3 dB, −3 dB)

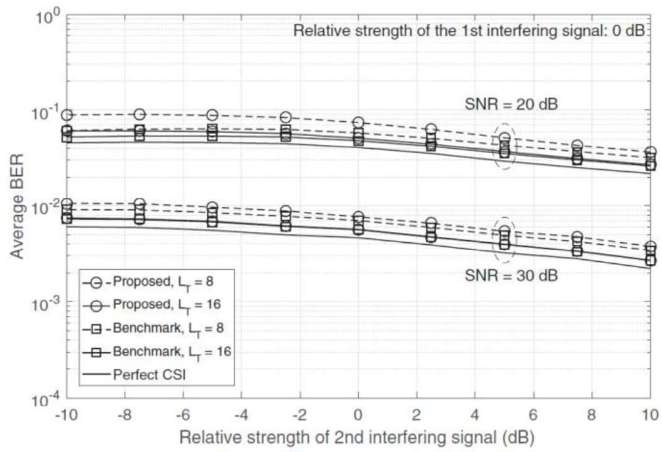

Fig. 21. Average BER performance under different interference conditions

The flow chart of the proposed scheme is illustrated in **Fig. 18**. For each quantized channel search (QCS), the quantized channels are first generated, and a local search with iterative signal detection and RLS channel estimation that starting from each quantized channel is added to accelerate the convergence. In addition, a recalculation scheme is introduced to avoid inaccurate channel estimates due to local minima. Using the estimated channels, the proposed scheme performs multiuser detection (MUD) of the data sequences in order to cancel the interference.

Computer simulations show that the proposed scheme outperforms a conventional scheme based on the Generalized Viterbi algorithm (GVA) with reduced computational complexity on average, and can achieve almost the same average bit error rate (BER) performance as the benchmark (MUD with channels estimated from known training sequences of both the desired signal and the interfering signals) with sufficiently long training sequences, while reducing the computational complexity significantly compared with the full search for all interfering signal candidates during the training period.

Figs. 19 and **20** show the average BER performance of the proposed scheme, when 2 interfering signals exist. The average power of interfering signals are 3 dB stronger and 3 dB weaker than the desired signal, respectively. The length of the training sequence, L_T, varies from 4 to 16. The number of survivor at each stage for GVA is set to 32. **Fig. 21** shows the average BER performances when the strength of the first interfering signal is the same as the desired signal, and the strength of the second interfering signal varies from −10 dB to 10 dB. It can be observed that the proposed scheme achieves almost the same performance as the benchmark under the various conditions of the interference.

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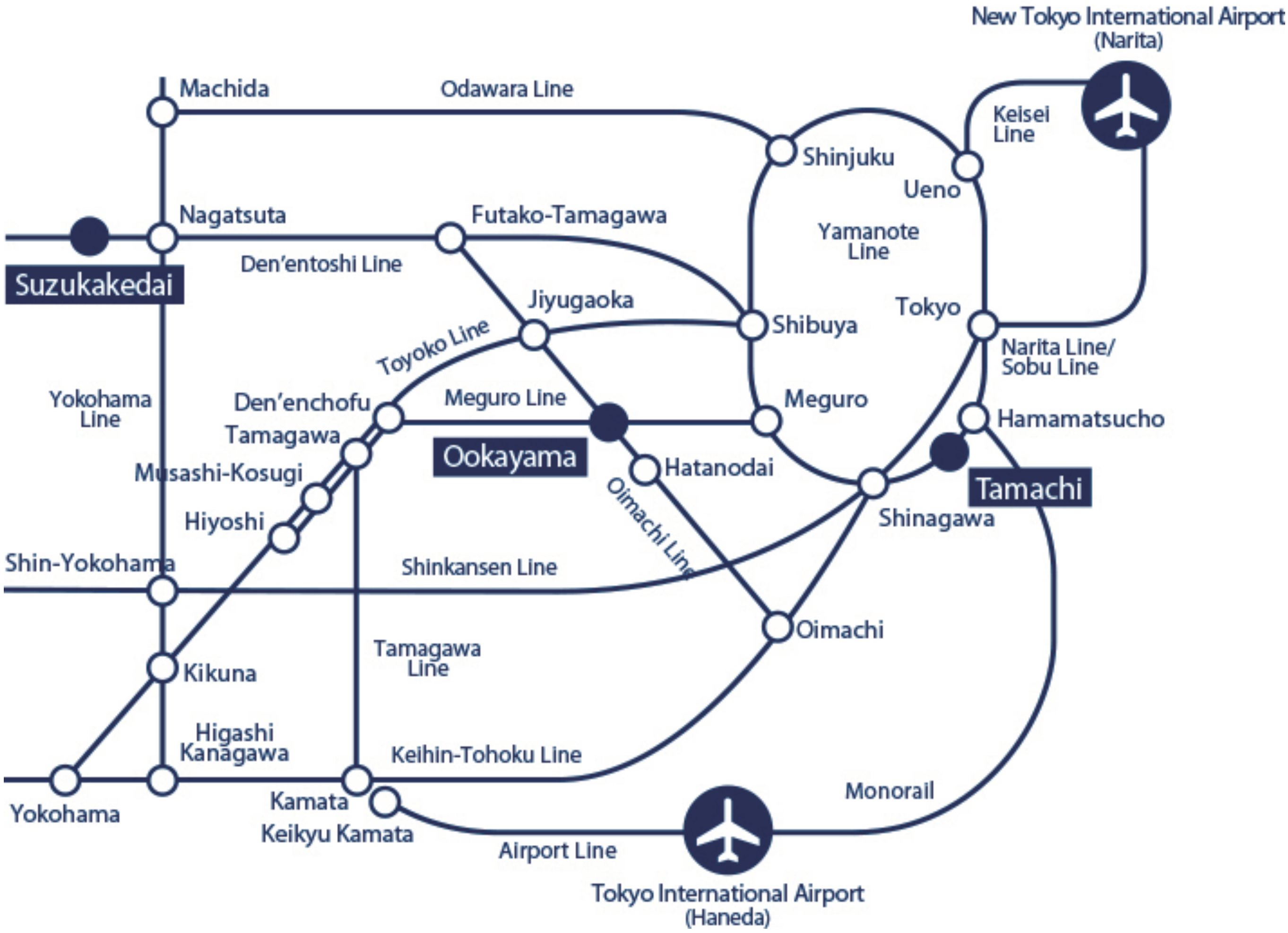

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2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550, JAPAN